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INVESTIGATION OF ACTIVE CONTROL OF COMBUSTION INSTABILITIES IN LIQUID PROPELLANT ROCKET MOTORS

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Overview

After developing an active control system (ACS) that uses a gaseous fuel actuator and demonstrating its effectiveness in the suppression of combustion instabilities in a combustor that burned gaseous reactants, efforts under this program focused on the development of an ACS that uses a liquid fuel actuator (LFA). The near term goal of these efforts is to use the developed ACS to demonstrate active control of combustion instabilities in a combustor that burns liquid fuel. The long-term goal of the program was to develop an ACS that could be used to control combustion instabilities in liquid, solid and hybrid rockets using either a liquid fuel or liquid oxidizer. It was also expected that the developed ACS will find applications in a wide variety of combustion systems e.g., jet engines, in addition to rocket combustors. This report summarizes the accomplishments of this three-year program.

The developed ACS controls instabilities by periodically modulating the injection rate of a small amount of a liquid fuel, a liquid oxidizer or a liquid monopropellant into the combustion chamber with a proper phase with respect to the unstable pressure oscillations. This action either reduces the effectiveness of the primary mechanism that drives the instability, generates secondary heat addition oscillations within the combustor out of phase with respect to the unstable oscillations, or both. To achieve this goal using active modulation of a liquid fuel is much more difficult than with a gaseous fuel, because combustion of a liquid fuel involves additional processes; i.e., the atomization and vaporization of the liquid fuel. These atomization and vaporization processes require additional time and are, thus, expected to increase the phase shift between the heat release oscillations and control signal to the actuator. Since active control of unstable combustors critically depends upon the ability to control the phase of the secondary heat release oscillations, which were expected to depend upon the liquid fuel atomization and vaporization processes, one of the main objectives of this study was to develop an understanding of the dependence of the phase of the secondary heat release oscillations upon the liquid fuel atomization and vaporization processes. In addition, this study set out to determine the feasibility of using a liquid fuel in active control of combustion instability.

It is critical that the LFA that supplies the secondary fuel exhibit a fast response; i.e., the time elapsed between the instant at which the control command was issued and the occurrence of heat release oscillations should be as short as possible. In addition, the injector should provide high

quality atomization over its entire range of flow rates. However, since the atomization and evaporation processes require a finite period of time, which is of the same order as time delay needed for suppression, the use of a liquid fuel in active control presented significant challenges. Specifically, this study had to develop an ACS that employs a liquid fuel to generate secondary heat release oscillations with a total delay of the same phase delays produced by ACS that uses a gaseous fuel to attain active control. To attain this goal, it was necessary to develop an understanding of the dependence of the control system phase delay upon the atomization, vaporization and mixing processes.

Another important issue is the fraction of the fuel injected by LFA that provides an oscillating heat release with the desirable phase shift. Ideally, to minimize the size and weight of the ACS all or most of the fuel supplied by the LFA should release its energy within a specific (and short) combustor region and at a specific instant (or a short time interval) during the unstable cycle. This will also minimize the amount of the secondary fuel that must be used to attain control. Concentrating the secondary heat release oscillations within a short distance is difficult to attain with a liquid fuel because of the wide distribution of the size and velocities of the liquid droplets within its spray, which would tend to distribute the combustion process along the combustor. Consequently, the oscillating heat release process provided by an ACS that employs a liquid fuel may be viewed as consisting of a series of point oscillators. Each oscillator in this series is characterized by its own amplitude and phase shift in respect to the unstable pressure oscillations. This "spreading" of the control heat release oscillations can be so large that part of the injected control fuel may drive rather than damp the instability. Consequently, developing a capability to "concentrate" the location of the secondary heat release process was another important objective of this study.

Practically, all previous experimental and theoretical studies of active control by oscillating fuel injection have made an assumption that active control is attained by generating heat release oscillations that are out of phase with respect to the unstable combustor oscillations. This view ignores the effect of the control action upon the primary mechanism that drove the instability. Another approach for stabilizing the combustor is to reduce the effectiveness of the primary mechanism that drives instability. If proven effective, this control approach may be advantageous in aerospace applications of active control as the ACS could then be incorporated into the engine's injection system; i.e., active control would be attained by modulating the

injection rate of a fraction of the fuel. Properly executed, such an approach could be employed to reduce the effectiveness of the mechanism that drives instability.

In response to the above described needs and in view of our inability to accurately model the combustion of steady and unsteady sprays, combustion processes produced by modulating the injection rate of liquid sprays were investigated experimentally under this program. Specifically, this program set out to develop an understanding of the dependence of the heat release oscillations (i.e., its spatial and temporal distributions) upon the characteristics of the generated sprays and mode of operation of the LFA. Attaining the needed data required the development of a new experimental set up with capabilities for measuring the spatial and temporal distributions of the combustion process. This was attained using a chemiluminescence scanning technique (CST) that can characterize the heat release oscillations in narrow slices of the reaction zone along the combustor, and using a Phase Doppler Particle Analyzer to characterize the oscillating spray. The remainder of this report briefly summarizes the important results attained under this program. Detailed descriptions of these studies are provided in the papers that are included in the appendix of this report.

Summary of Activities and Accomplishments During the Report Period

The initial design of the LFA is shown in Figure 1. This design employs all the pressure rise provided by the fuel pump to atomize the liquid fuel while controlling the liquid flow rate by changing the cross sectional area of the orifice that supplies the liquid to the combustor. A prototype of the LFA shown in Figure 1 was developed and tested. These tests revealed that while the LFA could rapidly modulate the liquid injection rate, the direction and shape of the generated spray were very sensitive to small deviations in the concentricity of the conical section at the downstream end of the stem relative to the orifice seat. Another problem of concern was the frequent contact between the conical section and its annular seat, which could damage the seat after many cycles of operation.

In view of the above concerns about the LFA shown in Figure 1, it was decided to develop another LFA that would be devoid of these problems. This LFA is shown in Figure 2. It essentially consists of a pintle type injector /on the bottom/ that is coupled to the (magnetostrictive) Etrema actuator /on top/. Tests with this LFA showed that it can operate over a wide range of fuel flow rates; i.e., 0-5 g/sec of fuel with a supply pressure of 1200 psi. In this actuator design, the geometry of the atomizing orifice (6) is not affected by the movement of the pintle. Instead, the up and down movement of the pintle varies the cross sectional area of the passage (4), which in turn, changes the hydraulic resistance of the cavity. The variations in the flow resistance of passage (4) change the pressure difference between the supply plenum (3) and the cavity (5) just upstream of the atomizing orifice (6). The variations in the pressure in the cavity (5) change the flow rate through the atomizing orifice (6). The advantage of this design is that the frequent on-off action of the pintle imparts no strain on the thin walled atomizing orifice. Instead, the mechanical strain is imparted to the surfaces surrounding passage (4), whose relatively larger contact surface area can dissipate the stresses that form during contact. The main disadvantage of this design is that the flow rate is controlled by pressure drop across the atomizing orifice. Consequently, a lower flow rate requires a smaller pressure drop, which in turn, results in poorer atomization. This effect presents no problems when this injector operates at an on-off mode in which the flow passage is either fully closed or wide open. It was observed however, that when this LFA sinusoidally modulated the fuel injection rate, it provided poor atomization during part of the cycle. To correct this problem, the signal to the actuator was modified by the addition of a high frequency signal of about 5000 Hz, which enhanced the atomization. The latter is particularly important when the LFA supplies a low fuel flow rate, when the pressure drop across the LFA is low. Extensive results describing the performance of this LFA are presented in Ref. [1], which is included in the appendix of this report.

Subsequent studies investigated the heat release oscillations generated in response to modulations in the liquid fuel injection rate in open loop and close loop control experiments. These experiments utilized a newly developed experimental set up (see Figure 3), which employed a quartz combustor (see Figure 4). A quartz combustor was used because it enables viewing the whole combustion zone in reactive tests and the spray in cold tests. Chemiluminesscence scanning and a Phase Doppler Particle Analizer were used to characterize the heat release from the oscillating combustion process and the oscillating spray in the reactive

and cold flow experiments, respectively. Initially, the dependence of the spatial and temporal distributions of the oscillating combustion process heat release upon the LFA setting and design were investigated. The goal of this study was to determine the LFA design and operating conditions that produce a highly compact flame that oscillates with a high amplitude and nearly constant phase, as such a flame would effectively damp unstable combustion oscillations. The reactive studies determined the characteristics of the oscillatory combustion process generated by various modes of fuel modulation by the LFA. Specifically, these studies determined the characteristics of the oscillatory flame generated by square wave modulation over 170 800Hz frequency range and duty cycles changing from 20% to 80% (the duty cycle describes the percentage of time during the cycle, that the LFA is open). The reactive flow studies have shown a good response of the flame to the fuel flow rate modulation in all investigated frequency and duty cycle ranges. These experiments showed that 70-80 percent of the energy content of the modulated fuel stream could be effectively used to damp unstable oscillations in 170-600Hz frequency range. The results of the reactive studies were correlated with the cold flow characterizations of the LFA sprays. These correlations showed that the spray droplet size and velocity distributions affect the fraction of the secondary fuel that burns in an oscillatory manner. These studies suggest that the spray characteristics can be optimized to match the required performance of the oscillating combustion process. This study also showed that the most effective control flames were achieved when a cluster of fine droplets penetrated up to the center of the recirculation zone of the flame holder and then burned in a short time burst, as illustrated by high speed photography. Extensive results of this study are presented in Ref. [2], which is included in the appendix of this report.

The final study under this program investigated the suppression of combustion instabilities by reducing the effectiveness of the primary mechanism that drives the instabilities. This was accomplished by first investigating the characteristics of the unsteady combustion process during unstable operation of the combustor and then, investigating whether modulation of the fuel injection rate would decrease the amplitude of the unstable oscillations. This study showed that during unstable operation, oscillations of the heat release in the entire reaction zone occur in phase with the pressure oscillations in the combustor (i.e., a flat phase profile). This indicates that during unstable operation, heat release oscillations all along the combustor drove the instability. Next, the combustor was actively controlled in a close loop using an adaptive control

approach by oscillating the LFA's pintle in a prescribed manner. These oscillations periodically changed the droplet size and velocity distributions thus, generating heat release oscillations in one part of the combustor out of phase with respect to the heat release oscillations in another part of the combustor. Comparison of the oscillatory heat release oscillations in the unstable and controlled combustors showed that the former was characterized by a flat, nearly constant phase distribution, while the latter was characterized by a continuously increasing phase distribution. This comparison also showed that modulating the fuel injection rate reduced the amplitude of the most intensive mode by a factor of two. Typical results of this study are shown on Figures 5 through 8. Detailed descriptions of this study, its results and related theoretical studies are presented in Ref. [3]. This study suggested that the effectiveness of an ACS, which uses modulation of the main fuel injection rate, can be increased by optimization of oscillating spray characteristics.

Finally, these efforts also developed and tested a light weight LFA for use in practical rocket motors and air breathing propulsion systems. This LFA (see Figure 9) uses a low voltage piezoelectric actuator to oscillate the LFA's pintle. Suppression effectiveness attained using this LFA was comparable to that demonstrated earlier under this program with the magnetostrictive LFA. This is significant as the weight and dimensions of the new LFA are much smaller than those of the previous LFA (see Fig. 10).

Current and Future Activities

Current and future research activities are divided into two main efforts. The first effort includes development and fabrication of the new model combustors that will be used to optimize the performance of the ACS and LFA using measurements of the oscillating flame and oscillating spray characteristics. In contrast to the combustor used in the reported studies, which had one fuel injector, the developed combustor will have a primary, steady, fuel supply system and a secondary, actively controlled, fuel supply system. Under "normal" operation both fuel supply systems will operate in a steady mode. However, under unstable operation, the secondary fuel supply flow rate will be modulated to suppress the instability. Suppression will be achieved

as a result of the interaction of two oscillating heat release processes; i.e., main heat release process (naturally unstable) and the actively modulated, controlled heat release process. The second model combustor will include a new LFA design, which will modulate the liquid fuel flow rate by periodic oscillations of the pressure of atomizing gas (air) in the effervescent type liquid fuel injector (see Figure 11).

The second effort will develop a compact, light weight, LFA, which controls the liquid fuel flow rate by changing the cross sectional area of the orifice that supplies the liquid to the combustor. We denote this design as AVLFA (Area Variable Liquid Fuel Actuator). A schematic of the proposed AVLFA under experimental development is shown in Fig.12. Its main advantages are:

- The use of the hydraulic pressure to close the actuator thus minimizing to the seat by interactions with the ball.
- The natural "self centering" of the ball, which eliminates the need for another device/method for centering the ball.

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1. Y. Neumeier, E. Lubarsky, R., Heising, R., Israeli, O., Neumaier, M. and Zinn, B.T., "Liquid Injector Actuator for Control of Combustion Processes," AIAA 98-3540, 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Cleveland, OH, July 13-15, 1998.
2. R. Heising, E. Lubarsky, Y. Neumeier, and Zinn, B. T, "Experimental Characterization of an Oscillating Liquid Fuel Spray Combustion for Suppression of Combustion Instabilities," AIAA 2000-1024. Accepted for presentation at 38th Aerospace Science Meeting & Exhibit, Reno, NV, Jan. 10-13, 2000.
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Mohanraj, R., Neumeier, Y., and Zinn, B. T., "Characteristic-Based Treatment of Source Terms in Euler Equations for Roe Scheme," *AIAA Journal*, Vol. 37, No. 4, April 1999.

B.T. Zinn, and Y., Neumeier, "An Overview of Active Control of Combustion Instabilities," AIAA-97-0461, 35th Aerospace Sciences Meeting & Exhibit, Reno, NV, January 6-10, 1997.

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Neumeier, Y., Lubarsky, E., Heising, R., Israeli, O. and Neumaier, M., and Zinn, B. T., "Liquid Injector Actuator for Control of Combustion Processes," AIAA 98-3540, 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Cleveland, OH, July 11-13, 1998.

Graduate Students Participated in the Project

Yongee Liu, M.S. degree 1997
Rajendran Mohanraj, Ph.D. 1999
Raymond Heising, M.S. 1999
Friedhelm Kappei, Master Thesis, in cooperation with Stuttgart University 1999
Jaeyeon Lee, Ph.D student, in progress.
Cliff Jonhson, Ph.D student, in progress..

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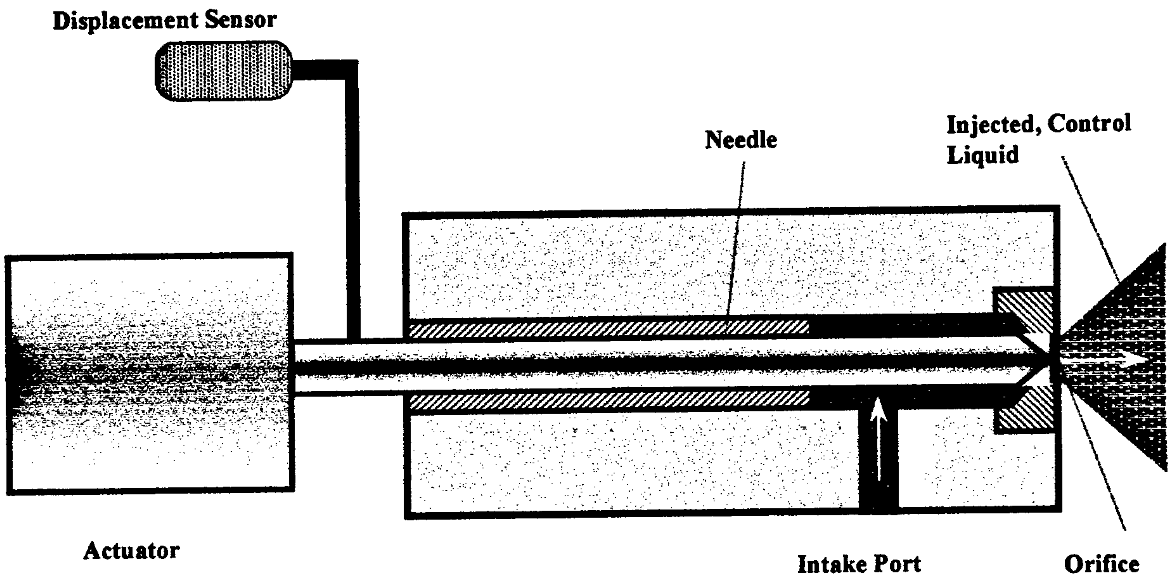


Figure 1. A Schematic of LFA with Direct Control of the Area of the Spray Orifice.

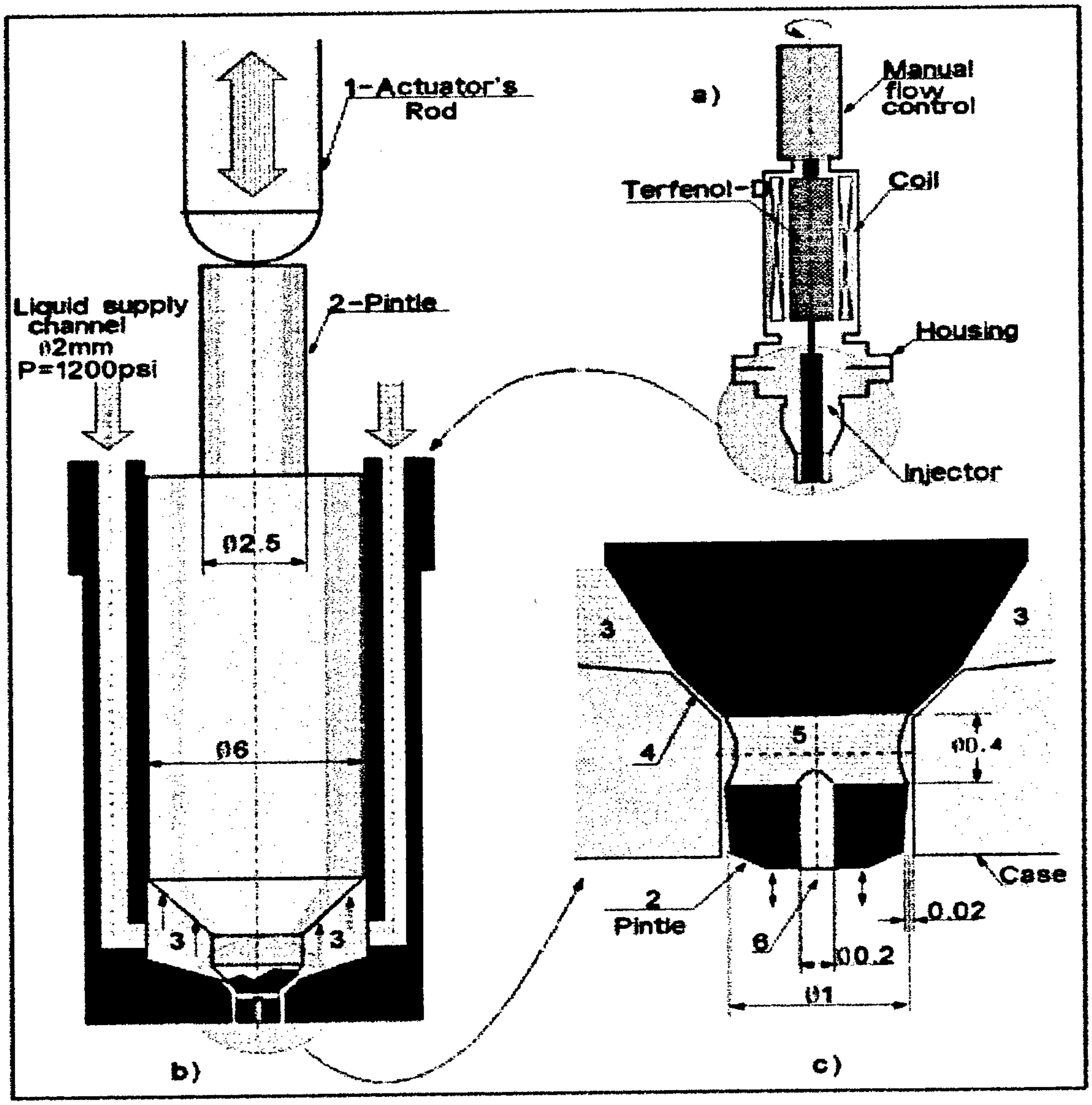


Figure 2. A Schematic of LFA.

a) General Configuration; b) Pintle Injector; c) Pintle Termination;

Designations:

1. actuator rod;
2. pintle;
3. high pressure supply;
4. cone passage;
5. cavity;
6. atomizing orifice.

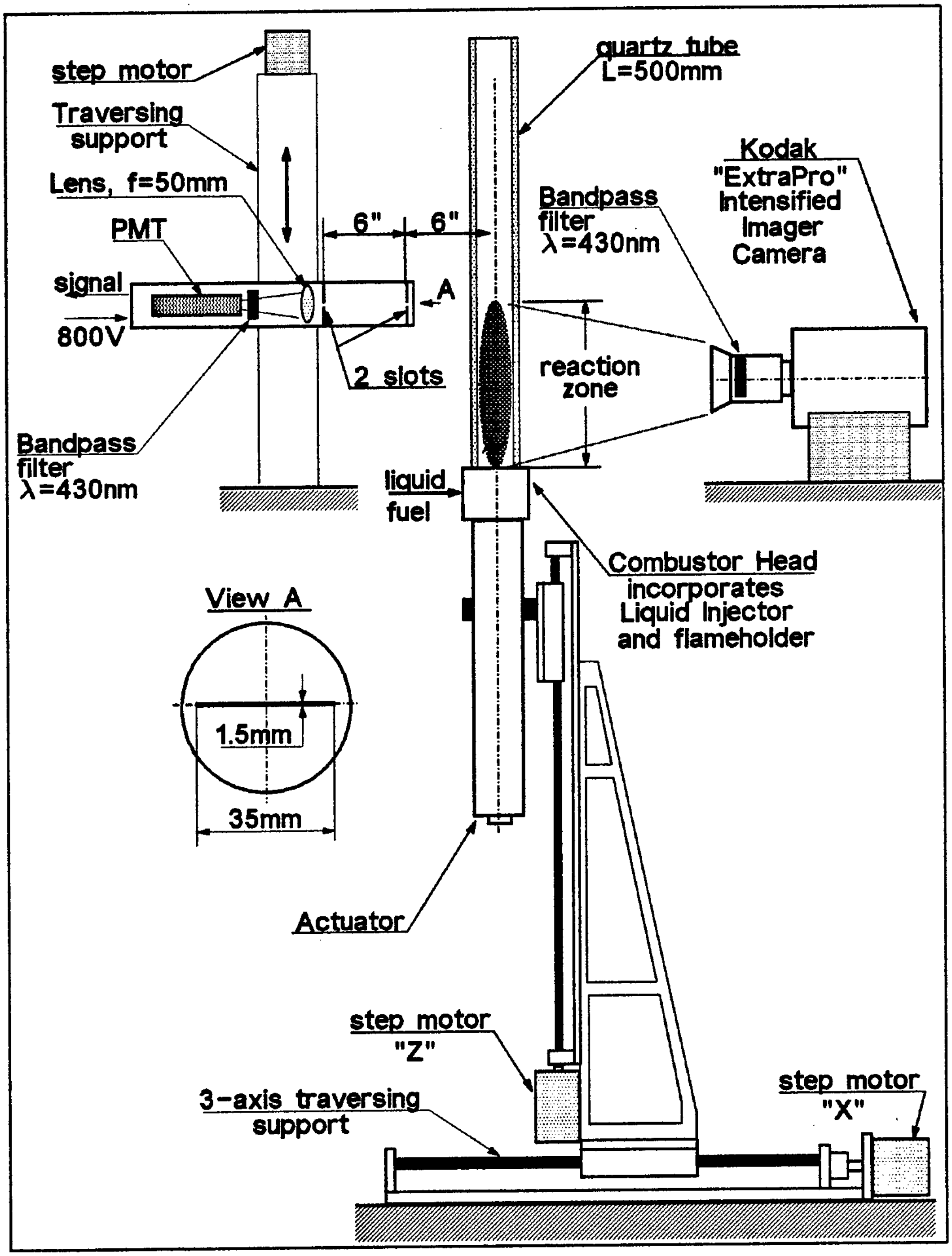


Figure 3. The Arrangement of the Diagnostic Equipment.

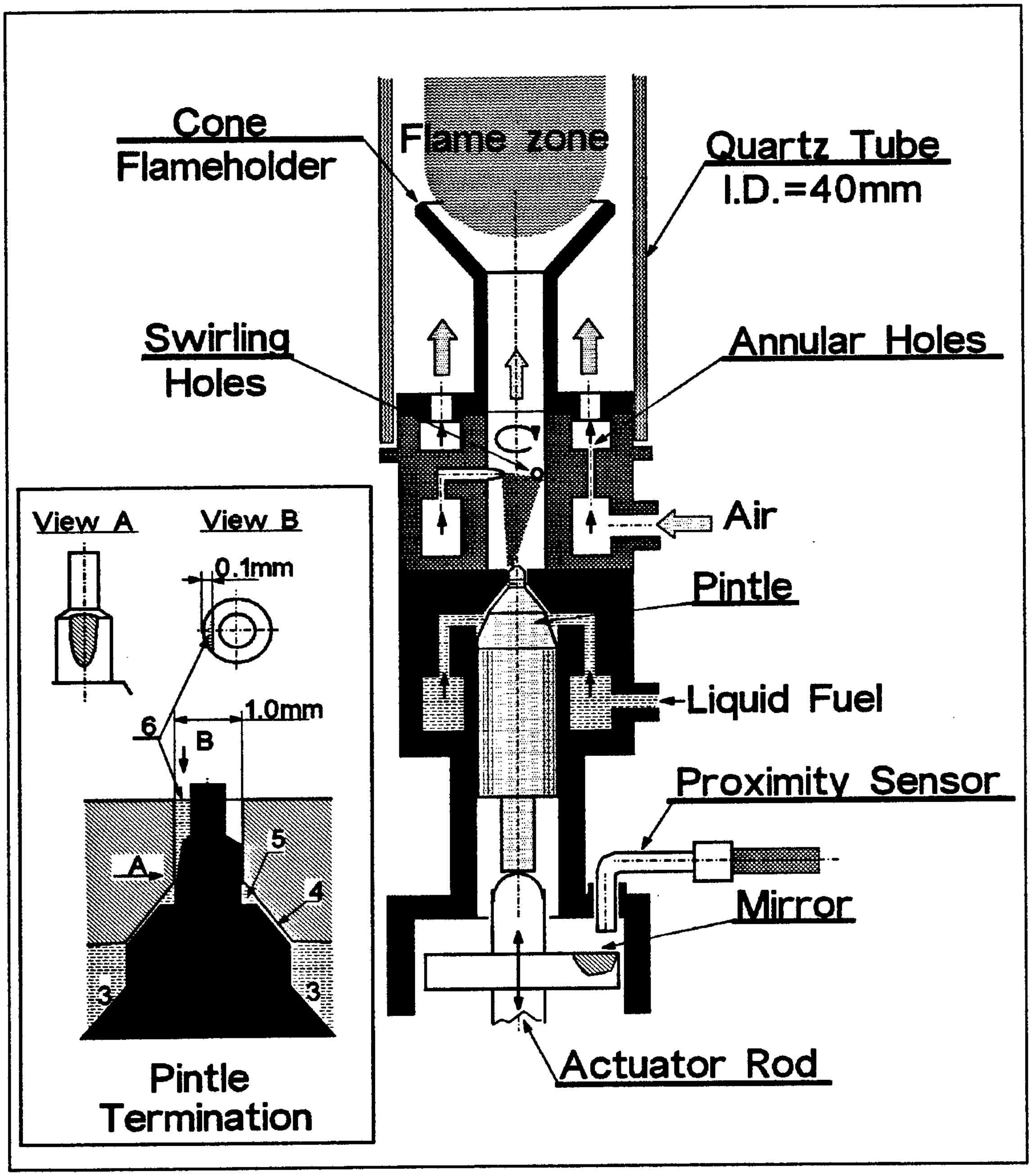
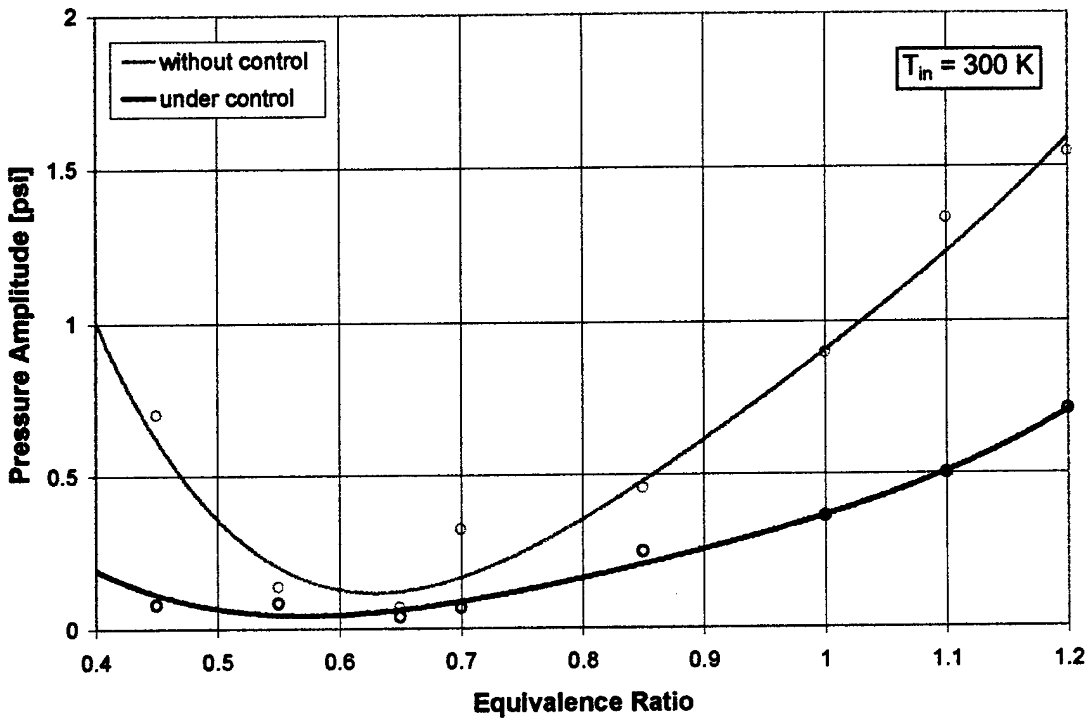
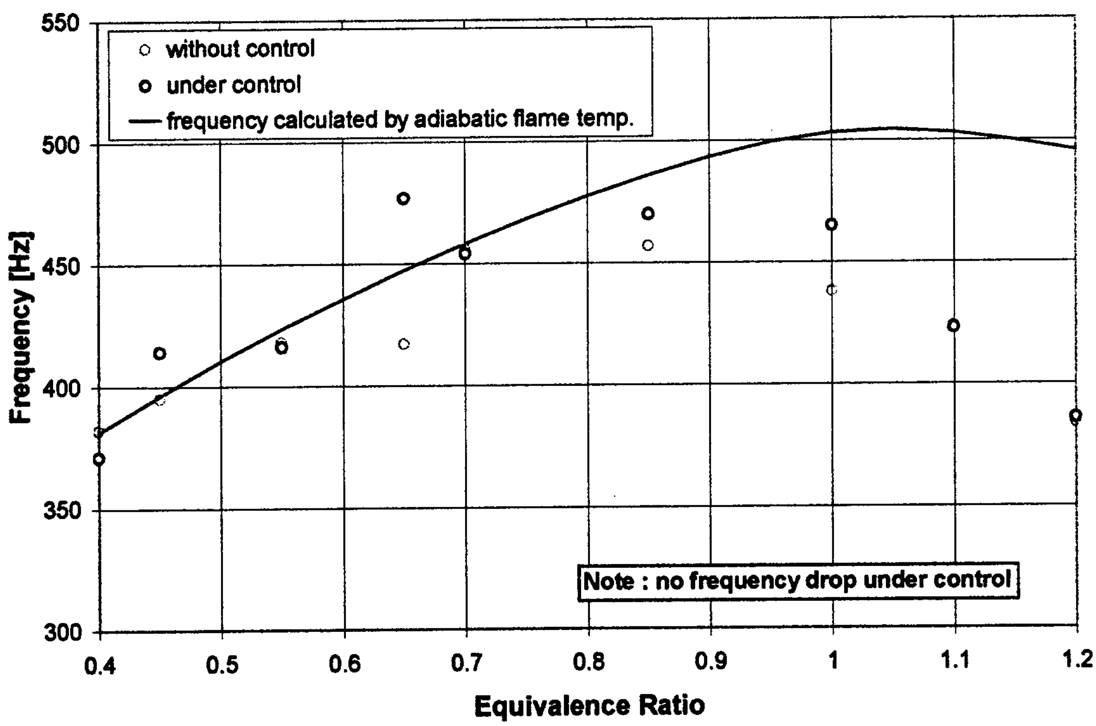


Figure 4. The Combustor Head Configuration.



(a)

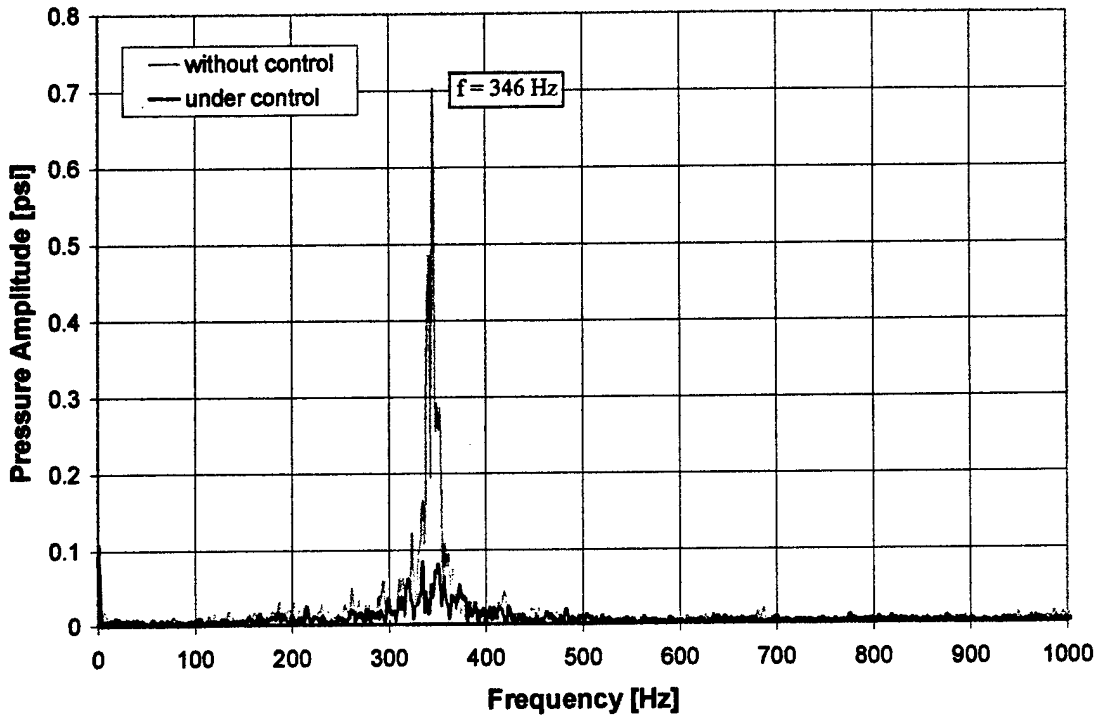


(b)

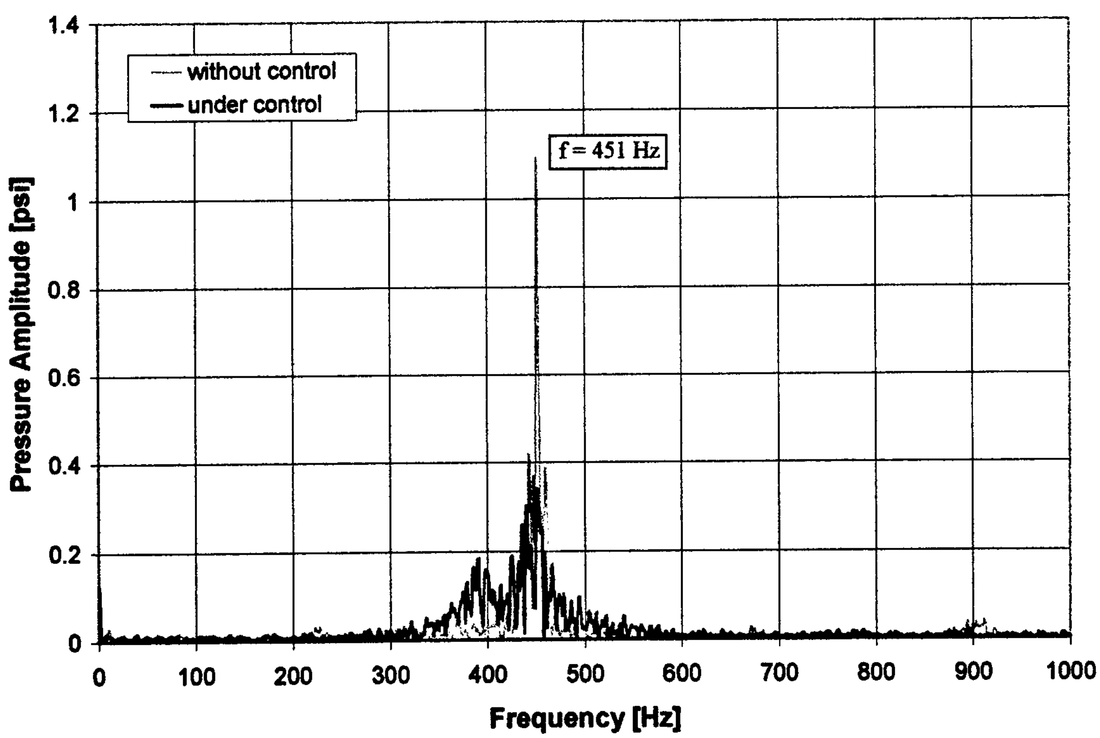
Figure 5. Effect of Actively Controlled Modulation of the Liquid Fuel Flow on the Pressure Oscillations in the Model Combustor.

(a) Pressure Amplitude vs. Equivalence Ratio

(b) Frequency of Pressure Oscillations vs. Equivalence Ratio

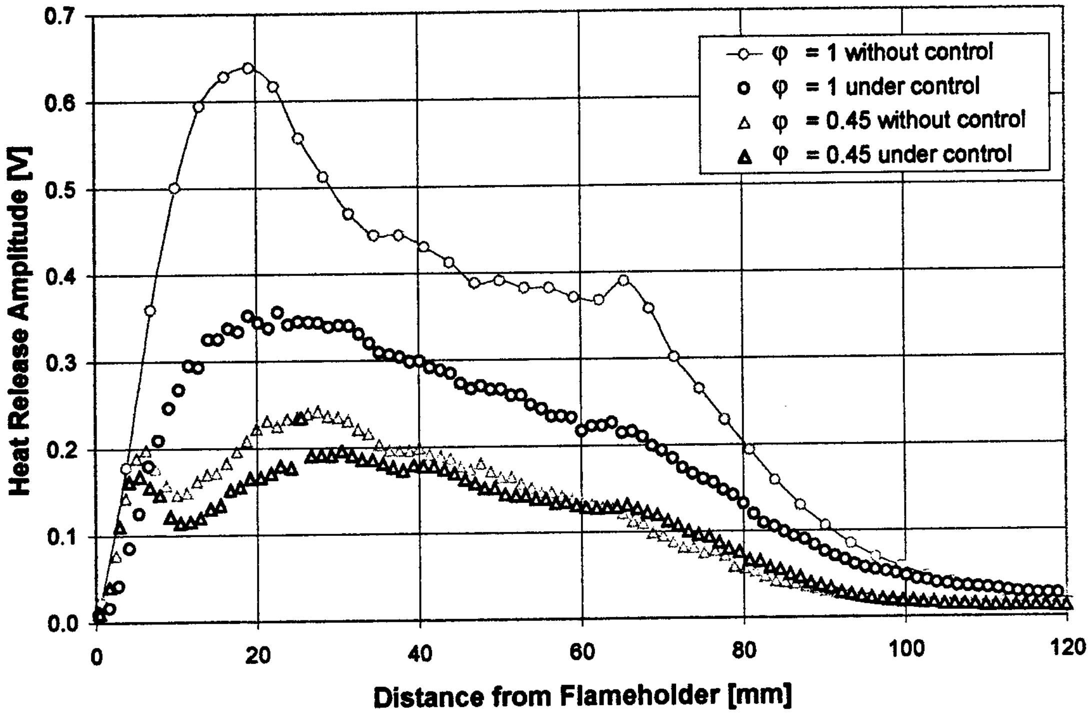


(a)

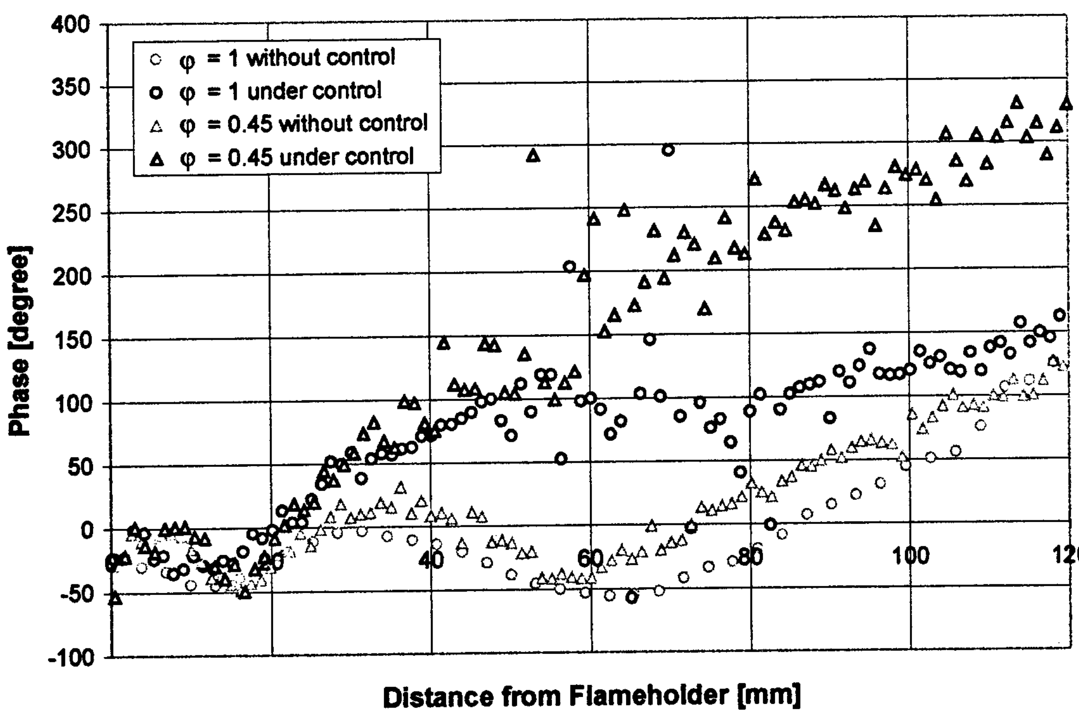


(b)

Figure 6. Effect of Actively Controlled Modulation of the Liquid Fuel Flow on the Amplitude Spectra of the Pressure. (a) Suppression of the "Lean" Instability ($\varphi = 0.45$) (b) Suppression of the "Rich" Instability ($\varphi = 1$)



(a)



(b)

Figure 7. Effect of Actively Controlled Modulation of the Liquid Fuel Flow on the Axial Distribution of the Heat Release Oscillations along the Reaction Zone.
(a) Heat Release Amplitude Profile (b) Phase Profile

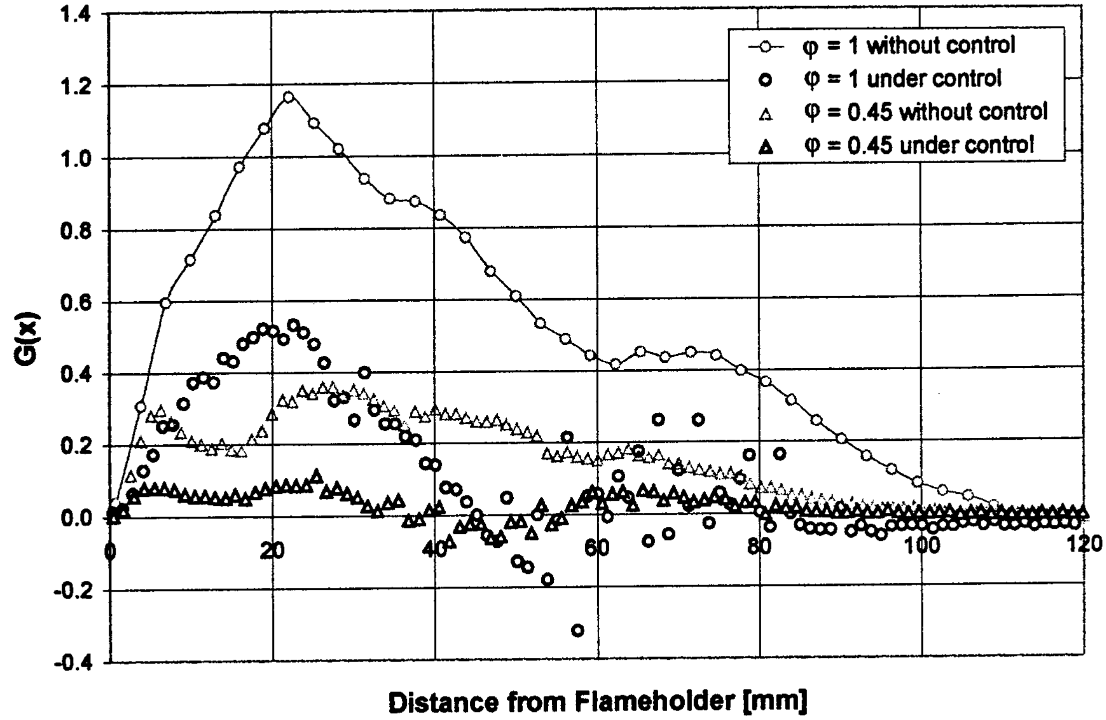


Figure 8. Effect of Actively Controlled Modulation of Liquid Fuel Flow on Rayleigh Index Distribution along the Reaction Zone. - the area under each curve indicates the driving ability of the oscillating heat release.

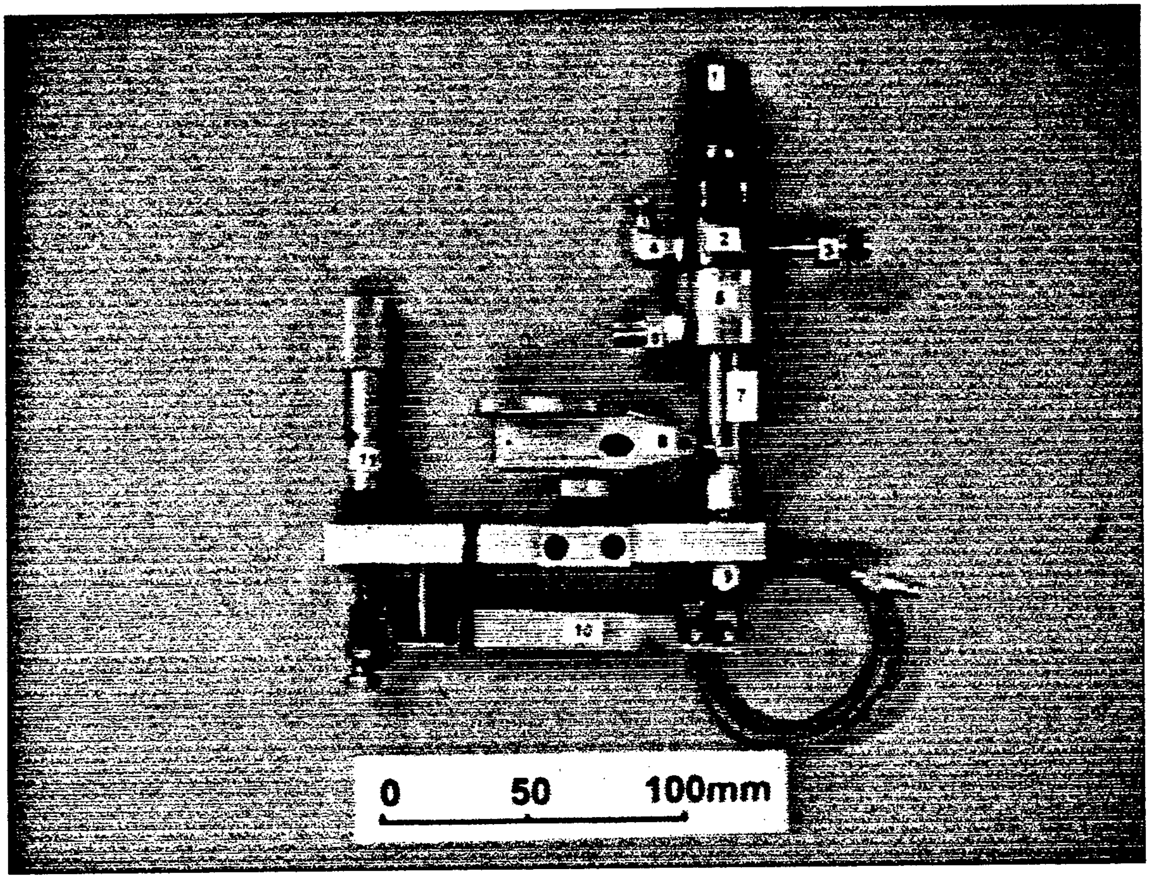


Figure 9. Detailed View on the Piezoelectric Actuator.
Designations
1. Pintle injector;
2. Fuel distributor;
3. Fuel line;
4. Bleeding drain line;
5. Actuator housing;
6. Cooling air line;
7. Rod;
8. Indicator (for calibration only);
9. Piezoelectric translator;
10. Rocker;
11. Micrometer (for manual adjustment).

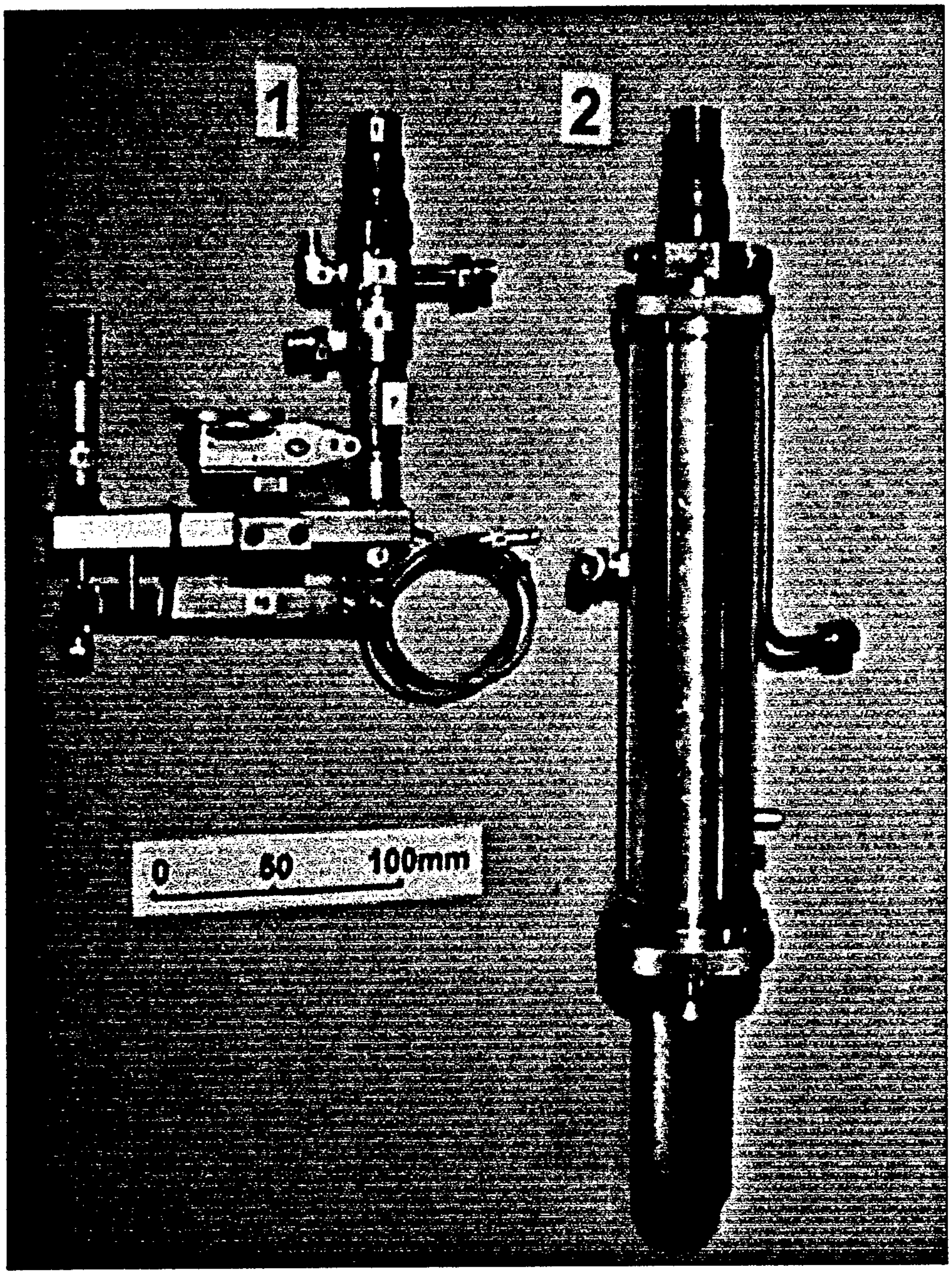


Figure 10. Comparison of Dimensions between the Piezoelectric Actuator(1) and the Magnetostrictive(2) Actuator.

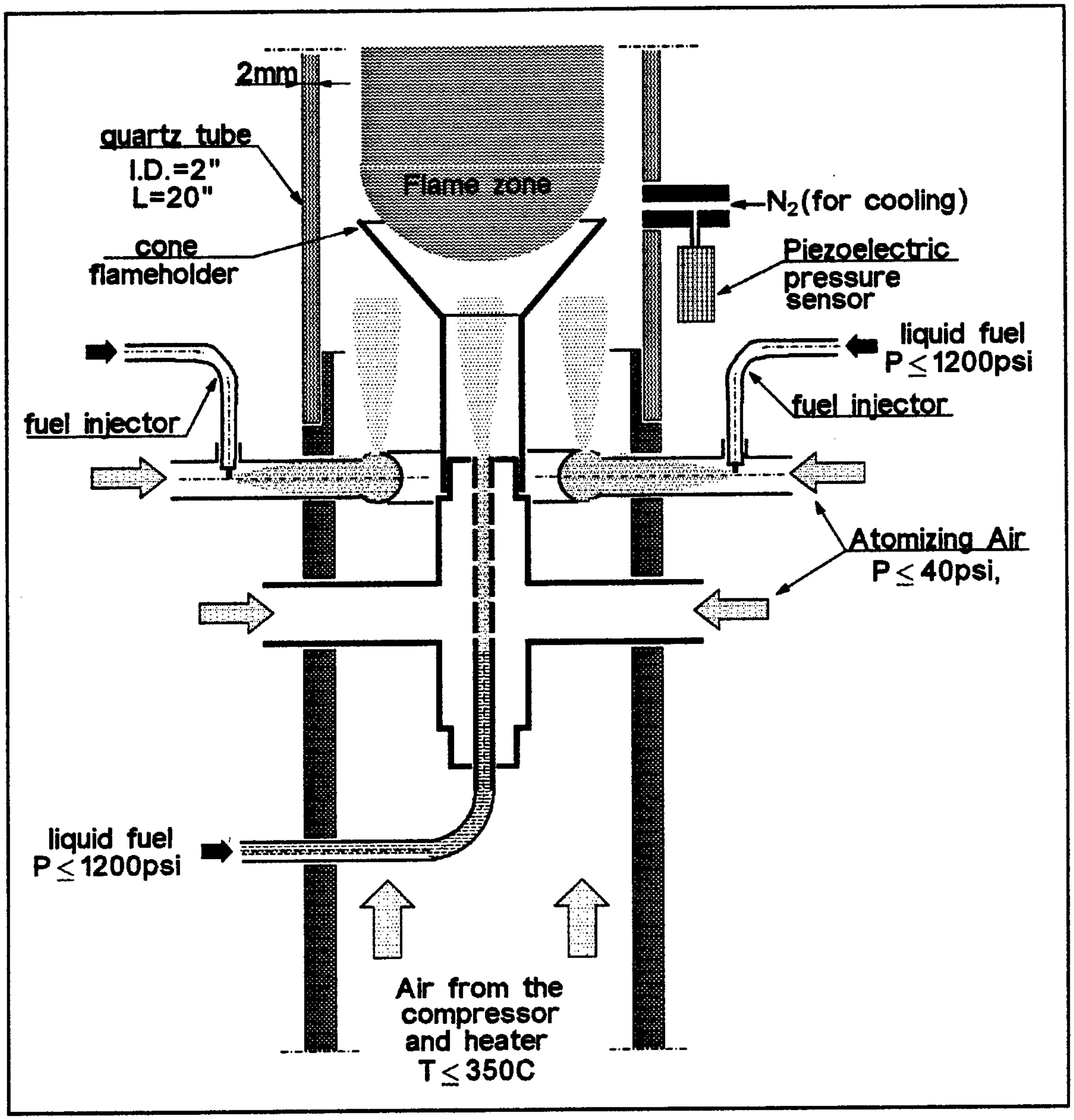


Figure 11. Combustor Head with the Effervescent Liquid Fuel Injector for Control of Combustion Instability.

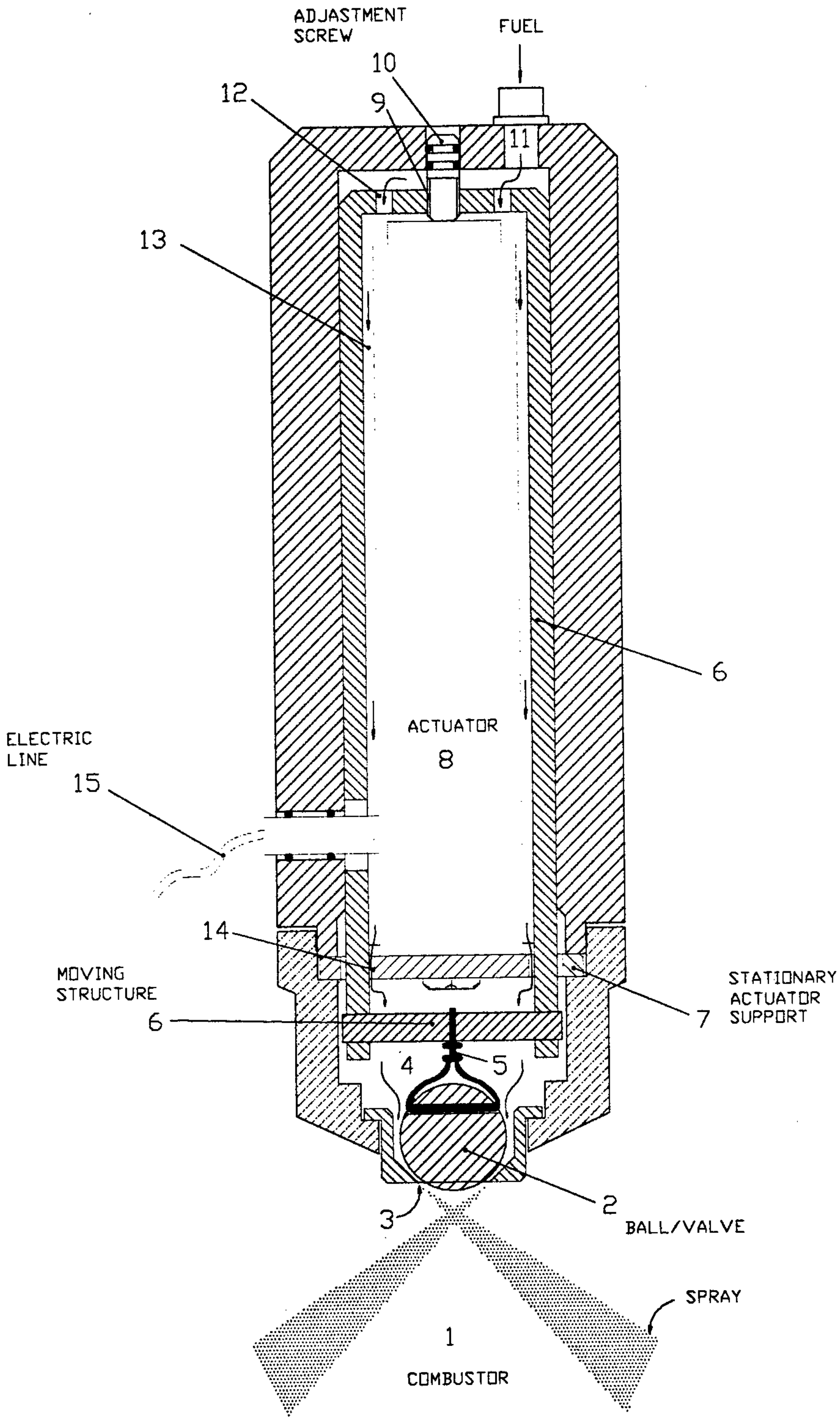


Fig 12. A Schematic of LFA with Direct Control of the Area of the Spray Orifice

APPENDIX

AIAA 98-3540

Liquid Injector Actuator for Control of Combustion Processes

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Liquid Injector Actuator for Control of Combustion Processes*

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Abstract

This paper describes the performance of a liquid injector actuator (LIA) that was developed for controlling combustion instabilities in combustors that use (or could use) a liquid fuel or oxidizer. The performance of the LIA was investigated in cold and reactive flow studies. The cold flow studies determined the characteristics of the LIA's sprays over ranges of fuel flow rates and sinusoidal modulation frequencies. These have revealed that: 1. modulating the spray at specific frequencies (e.g., 2400 Hz) optimizes the atomization, 2. modulation atomizes the injected liquid at low flow rates for which no atomization occurs under steady operating conditions, and 3. modulation generally reduces the sprays' arithmetic and Sauter mean droplets diameter (SMD) over most operating conditions. The reactive flow studies have shown that the developed LIA can produce large amplitude reaction rate and heat addition oscillations that should be effective in active control of combustion instabilities. The measured frequency dependence of the heat release oscillations produced by the LIA was compared with corresponding data obtained with a gaseous fuel. These comparisons showed that liquid fuel produces a longer phase delay, which was expected, and a larger gain, which was not expected. The latter suggests that a low gain may not be a problem for active controllers that use liquid fuels to damp combustion instabilities.

Introduction

This paper describes the results of a study of the performance of a liquid injector actuator (LIA) developed for active control of combustion instabilities in propulsion systems in general and chemical rockets in particular. Specifically, it describes the results of cold flow studies of the characteristics of the LIA's sprays, and "hot" flow studies of the reaction rate and pressure oscillations produced by the LIA in open loop tests in a small scale rocket combustor simulator. When employed as the actuator of an active control system (ACS), the LIA would modulate the flow rate of either a fuel or an oxidizer stream in a manner that would produce combustion process heat release oscillations that would damp the instability[1, 2]. The development of the investigated LIA was stimulated by results of earlier studies[2-4] that had demonstrated effective control of combustion instabilities with a gaseous fuel injector actuator, and the realization that active control of combustion instabilities in practical propulsion system would require modulation of a liquid stream with a LIA.

Combustion instability occurs when an oscillatory combustion process excites large amplitude pressure oscillations of one or more natural acoustic modes of the combustor. According to

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Combustion instability occurs when an oscillatory combustion process excites large amplitude pressure oscillations of one or more natural acoustic modes of the combustor. According to Rayleigh's criterion[5], unstable pressure oscillations are driven by combustion process heat release oscillations when the magnitude of the phase difference between these pressure and heat release oscillations is less than 90 degrees. Combustion instability occurs when the driving provided by the combustion process is larger than the inherent damping of the oscillations by, for example, viscous processes and acoustic energy radiation through the nozzle. Rayleigh's criterion also indicates that unstable pressure oscillations could be damped by generating heat release oscillations within the combustor that are 180 degrees out of phase with respect to the unstable pressure oscillations. This realization had stimulated interest in the development of ACS that modulate the injection rate of a fraction of the fuel to produce "out-of-phase" heat release oscillations within the combustor[1-4].

Since the investigated LIA will be incorporated into an ACS similar to the one that successfully damped combustion instabilities with a gaseous fuel actuator[2-4], the operation of this ACS is briefly discussed in what follows. It consists of a sensor, an observer, a controller and an actuator. The sensor is a pressure transducer that measures the combustor's pressure oscillations. The measured pressure signal is transmitted to the observer where a wavelet-like analysis is employed to determine the frequencies, amplitudes and phases of the "most unstable" (i.e., largest amplitude) combustor modes in real time. These data are sent to the controller where the frequency dependence of the secondary (i.e., control) combustion process phase and gain (obtained in open loop experiments) is stored and used to determine the gain and phase of the control signal. The controller then sends the control signal to the fuel injector actuator that modulates the flow rate of a fraction of the burned fuel to generate secondary heat release oscillations within the combustor that damp the instability. This ACS was successfully demonstrated in a small scale gaseous rocket combustor that burns methane and air. It attenuated various, fully developed, combustion instabilities within periods of the order of 40 milliseconds by modulating 20 percent of the total fuel input at the frequency of the most unstable mode.

The success of these studies stimulated interest in investigating the performance of an ACS that would employ a similar control approach, but utilize a LIA instead of the gaseous fuel injector actuator. It is expected that this ACS would find applications in practical combustors that could use a liquid reactant to control their instabilities. For example, modulating the flow rate of a liquid oxidizer could potentially be used to control instabilities in liquid, solid and hybrid rockets.

This paper describes the configuration of the investigated LIA and initial results describing its performance. The first part of the paper describes the development and configuration of the LIA, the experimental setup developed for cold flow studies of the characteristics of the LIA's sprays, and the characteristics of sprays generated with and without modulations. The second part of the paper describes the results of open loop response tests that investigated the frequency dependence of the magnitude and phase of the heat release oscillations that were excited by the LIA in a small scale rocket motor by modulating the flow rate of the injected fuel. The latter are then compared with the corresponding data measured in open loop control tests with the previously developed gaseous fuel actuator[6].

The Liquid Injector Actuator (LIA)

Initially, we attempted to develop a LIA with a fuel injection orifice whose area could be controlled while keeping its pressure drop fixed. This required the development of a LIA whose pintle could oscillate up and down within a concentric conical cavity while maintaining very small tolerances between the oscillating pintle and surrounding casing walls. Unfortunately, this design was very sensitive to small eccentricities and the developed LIA produced non-symmetric sprays. Consequently, we changed the LIA's design and incorporated a commercial diesel fuel injector nozzle into the actuator, see Fig. 1. The developed LIA consists of a Teflenol D magnetostrictive actuator that is connected to a pintle-type injector, see Figs.1-a, b. Time dependent control of the liquid flow rate through the LIA is obtained by changing the current to a coil that surrounds the magnetostrictive actuator. The control signal changes the actuator's magnetic field, which, in turn, changes the length of the magnetostrictive rod **1**. As the actuator's length changes, it pushes the pintle **2** against a pressure force exerted by the liquid fuel that is supplied into the volume **3** between the pintle's conical termination and the LIA's casing. The resulting force imbalance sets the pintle in motion. As the pintle moves upwards, the annular clearance **4** between the two cones opens and allows liquid fuel to enter the plenum **5**, see Fig. 1-c. The pressure in the plenum **5** changes as the width of the cross sectional area of the annular clearance **4** changes, thus changing the pressure drop between the plenum **5** and the space below the LIA. This pressure difference forces the liquid through the 200μm diameter nozzle **6** at the downstream end of the pintle where it emerges as a spray.

The LIA uses three controllers. A "slow" one with frequency band well below those observed during unstable combustion but high enough to respond to required load changes, a "medium" controller that modulates the LIA's flow rate at frequencies in the range where combustion instabilities are expected (e.g., 50-1000 Hz) and a "fast" controller that modulates the pintle at high frequencies (e.g., above 1000 Hz) to enhance the liquid atomization. The mean flow control loop (i.e., the "slow" controller) is performed digitally on a PC that is equipped with I/O boards. A nozzle-type flow meter equipped with an electronic readout provides the feedback for this controller. Oscillating voltage signals from a wave generator provide the "medium" and "fast" controls. These signals are amplified and then fed along with the DC signal of the flow rate controller to the actuator.

Cold Flow Experimental Setup

Figure 2-a presents a schematic of the experimental setup that was developed and used to investigate the LIA's sprays under cold flow conditions. The LIA is mounted on top of a cylindrical pressure vessel with side widows that provide optical access for photography and laser beams from an Aerometrics Phase Doppler Particle Analyzer (PDPA) that was used to characterize the sprays. During a test, a low velocity air (i.e., about 1 m/sec.) is injected through the honeycomb section on top of the tank to provide a gas film that prevents misting of the windows by recirculated liquid droplets. After passing through the test section, the air and injected spray droplets move past a second honeycomb section below the test section and leave the system through an exhaust manifold and a liquid drain. The tank is mounted on a traversing mechanism that that can be precisely moved along three mutually perpendicular coordinates, thus

providing capabilities for placing any point in the spray at the intersection of the PDPA's laser beams.

The directions of the incident and transmitted PDPA's laser beams are shown in Fig. 2-b. Analysis of the collected beams determines the arithmetic and Sauter mean diameters of the spray whose definitions are given by

Sauter Mean Diameter = $D_{32} = \Sigma n_i d_i^3 / \Sigma n_i d_i^2$
Arithmetic Mean Diameter = $D_{10} = \Sigma n_i d_i / \Sigma n_i$

where n_i is the number of droplets in the size group "i", which corresponds to the mean diameter d_i. Analysis of the laser beams also determined the mean and rms components of the spray droplets velocities at the measurement location[7]. The sprays were also photographed while being illuminated with a regular or a stroboscopic lamp.

To determine the effect of the actuator's modulations upon the characteristics of the spray, the latter were determined with and without modulations, and the results were compared. The spray's characteristics are described in terms of the droplets' mean and rms velocities, and the arithmetic and Sauter mean diameters D_{10} and D_{32}, respectively. Each reported data point is based upon 5000 measurements, corresponding to the number of droplets crossing the measurement volume and providing a signal that can be analyzed.

Cold Flow Experiments Results

This section describes and compares the characteristics of the sprays produced by the LIA with and without high frequency modulation of the liquid stream. All the tests were performed with a diesel fuel supplied with a pressure of 1200 psi and all reported spray characteristics were measured in a plane 65 mm below the LIA, see Fig. 2-a.

In "steady" experiments, when the LIA was operated in the unmodulated mode, only the "slow" controller, which was used to maintain a desired mean fuel flow rate, was operated. On the other hand, combinations of "slow-medium" and "slow-fast" controls were used in the modulated tests, depending upon the test's objectives.

Figure 3 shows photographs of "steady" and "modulated" sprays. Both photographs were taken with the LIA operated with a "marginal" fuel injection rate of 0.5 g/s, representing the threshold of atomization under "steady" LIA operation, and the spray on the right was generated with a, "fast", 2400 Hz modulation. The photograph of the "modulated" spray was obtained by illuminating the spray with a stroboscopic lamp synchronized to the modulation frequency. Figure 3-a shows that the fuel emerges from the LIA as a dense liquid column, without any apparent atomization, under "steady" operation. In contrast, Fig. 3-b shows that modulating the same fuel flow rate at 2400 Hz atomized the fuel.

Figures 4-a, b present comparisons of the radial distributions of D_{32}, D_{10}, V_{mean} (i.e., mean droplet velocity) and V_{rms} (i.e., rms droplet velocity) obtained in "steady" and "modulated" tests with a fuel flow rate of .62 g/s. The "modulated" tests were conducted with a "fast" control signal whose rms amplitude and frequency equaled 0.3 Amps and 2400 Hz, respectively. These data were obtained over a radial distance $0 \le r \le 15\,mm$. Comparisons of the velocity data with the frequency of "encountering" droplets at various radial locations indicated that the radial dependence of the droplets number density was qualitatively similar to that exhibited by the mean velocity, V_{mean}, see Fig. 4-b, indicating that the droplets number density was significantly larger at the spray's centerline. Consequently, it was decided to present the effect of the

modulations upon the spray characteristics by comparing the histograms of D_{32}, D_{10}, V_{mean} and V_{rms} at the spray's centerline, see Figs. 4-c, d (histograms measured at other locations near the spray's centerline are similar to those presented in Figs. 4-c, d). An analysis of Fig. 4-a shows that the modulations reduced the magnitude of D_{10} over the whole measurement range from a maximum of around 100 µm under "steady" operation to a very low, nearly constant, value of around 40 µm (i.e., approximately a factor 2 reduction). Figure 4-a also shows that D_{32} approximately equals 140 and 100 µm in the vicinity of the spray's centerline (where most of the drops are present) in "steady" and "modulated" operation (i.e., a decrease of 10-30 percent), respectively, and that D_{32} increases and decreases with radial distance in the "modulated" and "steady" sprays, respectively. These results suggest that the modulation tends to produce larger diameter droplets near the periphery of the spray. This observation is confirmed by the histograms in Fig. 4-c; they show that the modulations produce a significantly larger number of smaller droplets near the spray's centerline. An examination of Fig. 4-b shows that the modulations increase the magnitude of V_{mean} and V_{rms} in the vicinity of the spray's centerline where most of the droplets are present; that is, V_{mean} increases from around 15-16m/s to 30-32m/s, and V_{rms} from 2-2.5m/s to 8m/s. Finally, Fig. 4-d shows that the modulation tends to increase the mean spray droplets velocities.

Figures 5-a, b present the frequency response of D_{32}, D_{10}, V_{mean} and V_{rms} at the spray's centerline in the 0-5000 Hz. frequency range. These data were obtained by supplying the actuator with a control signal whose rms amplitude equaled .25 Amps in all the tests. Figures 5-a, b show that the largest reduction in the arithmetic mean diameter D_{10} occurs at a frequency of 2400 Hz, and that D_{32}, V_{mean} and V_{rms} exhibit maxima at this frequency. Comparisons of the frequency response data with spray characteristics of the LIA when operated in a steady mode show that the modulations had a negligible effect upon the spray at frequencies of 750, 1500 and 3000 Hz. These results indicate that to minimize the sprays' mean droplet size, the LIA should be operated at one or more carefully selected frequencies, which undoubtedly depend upon the LIA's design.

Figures 6-a, b present the amplitude response of D_{32}, D_{10}, V_{mean} and V_{rms} at a distance of 3 mm off the spray's centerline. These data were obtained for rms control signal amplitudes in the 0-0.38 Amps. range, and the same modulation frequency of 2400 Hz. These plots show that D_{10} decreases and V_{mean} and V_{rms} increase, respectively, over ranges of magnitudes of the control signal's amplitude until they reach "saturation". It can be shown[6] that the magnitudes of the control signal amplitudes at which saturation occurs are due to interactions between the "slow" and "fast" controllers. In contrast, D_{32} remains practically constant over a range of low control signal rms amplitudes and starts increasing when the magnitude of the control signal exceeds a threshold magnitude of .2 Amps.

Finally, the minimum flow rates at which atomization was attained under "steady" and "modulated" operations were investigated. This study showed that the minimum flow rates for which satisfactory atomization was achieved approximately equaled 0.6 g/s and 0.4 g/s in "steady" and "modulated" LIA operation, respectively. This result is consistent with the photographs in Fig. 3, and shows that modulation at an appropriate frequency will increase the range of liquid flow rates for which satisfactory atomization could be obtained.

The operation of the investigated LIA can be understood by considering its design and the expected variations of the pressure drops in various parts of the LIA during a cycle of the oscillations, see Fig. 1. The LIA is supplied with fuel at a constant high pressure of 1200 psi. As

the pintle moves upward, gap 4 opens, thus lowering the pressure drop between spaces 3 and 5, see Figs. 1-a, c. This, in turn, increases the pressure drop across the nozzle 6, resulting in smaller spray droplets. Using the same reasoning, it follows that the spray's mean droplet size should increase as the pintle moves downward. Consequently, one would expect that the pintle's oscillations would produce complex bi-modal droplet distributions; large droplets should be generated when the pintle is near its lowest position and small particles when it is near its highest position. This hypothesis suggests that the formation of large diameter droplets could be minimized or controlled by supplying the actuator with different control signals. Instead of using a sinusoidal control signal, which has been used in this study, the actuator could be supplied with a signal that would keep the pintle at or near its highest position during a predetermined duty cycle and at its closed position during the remainder of the period. This, in turn, would assure a maximum pressure drop across the nozzle when it is open, thus minimizing the mean droplet size of the spray. Clearly, other control schemes could be devised to attain desired spray characteristics and combustor performance. Development of such control strategies would require additional investigations of the LIA response, undoubtedly involving considerations of the time dependent interactions of the pintle's motion, and the fluid mechanics within the complex LIA configuration.

Finally, the observation that the modulations decrease the minimum liquid flow rate for which satisfactory atomization is obtained, see Fig. 3, suggests that at a given liquid flow rate the pressure drop across the nozzle 6 is higher when the pintle is modulated. It is also possible that disturbances produced by the modulations destabilize the liquid flow and, thus, enhance liquid atomization at flow rates under which atomization is not attained under "steady" LIA operation.

Experimental Determination of the "Hot" LIA Response

Prior to incorporating the LIA into the ACS, it was necessary to demonstrate that it could produce combustion process heat release oscillations within a combustor over a range of frequencies that includes those observed in unstable combustors in response to a command signal. Furthermore, it was necessary to determine the frequency dependence of the gain (i.e., a measure of the amplitude of the excited heat release oscillations to be defined below) and phase difference between the heat release and the LIA's control signal oscillations. These data are stored in the ACS controller and used to determine the gain and phase of the control signal that is sent by the controller to the LIA to commence control[2-4].

The frequency dependence of the characteristics of the heat release oscillations generated by the developed LIA was investigated in this study in open loop response tests[6] using the experimental setup shown in Fig. 7. The LIA was installed at the center of the injection plate at the upstream end of a "very short", small scale, rocket simulator that had been previously used to investigate the active control of combustion instabilities[2-4]. All the burned fuel was supplied through the LIA and the combustion air through a number of choked orifices symmetrically located around the periphery of the injector plate. The downstream end of the LIA's nozzle, see Fig. 1, was recessed about 1 inch inside a hole in the center of the injector face. These studies were conducted in a "very short" combustor, whose fundamental longitudinal mode frequency was around 1500 Hz, to assure that the frequencies of its natural acoustic modes were outside the range of the investigated frequencies.

All of the reported tests were conducted with a relatively low LIA fuel flow rate of 0.57 g/s. In each test the LIA was modulated by the "medium" controller that modulated the fuel flow rate

at the investigated frequency (i.e., the LIA was not supplied with the 2400 Hz signal that was shown in the cold flow tests to optimize atomization even at low LIA liquid flow rates). Consequently, it is possible that the LIA generated poorly atomized sprays in these tests. It is also possible, however, that the sprays' atomization was improved by an interaction of the spray with the air jets that were injected into the combustor through the set of orifices around the central fuel spray. These issues will be investigated in future studies.

Ideally, one would want to determine the frequency response of the LIA from direct measurements of the amplitude and phase of the reaction rate oscillations generated in the combustor by modulating the LIA's fuel injection rate. In related studies by the authors[6] with an actuator that modulated the injection rate of a gaseous fuel this was accomplished by measuring the time dependence of the radicals (e.g., OH, CH or CC) radiation through a window that viewed the entire combustion region. Unfortunately, such direct radicals radiation measurements were not possible in this study because of the likelihood that "black body" radiation from soot, which often forms during the combustion of liquid fuels, would interfere with the radicals radiation measurements. Consequently, it was decided to determine the characteristics of the heat release oscillations indirectly from measured dynamic pressure data. This approach was shown to provide accurate combustion response data in a related investigation[6] of the open loop response of oscillatory methane combustion in the same combustor setup.

The pressure oscillations excited in the combustor by the heat release were measured with a pressure transducer that was installed on the combustor wall about two inches downstream of the reactants injection plane. Since the utilized combustor was very small and short, its characteristic dimension was much smaller than the wavelength of the excited oscillations, resulting in a uniform (instantaneous) pressure in the combustor. The needed heat release oscillations $\dot{q}'_{comb}$ were then determined from the measured pressure oscillations p' using the following relationship between the heat release and pressure oscillations, which was previously derived[6] using the combustor's energy equation:

$$\frac{2\gamma}{3\gamma-1}\frac{\dot{q}'_{comb.}}{\overline{\dot{m}}C_p\overline{T}_e}=\frac{p'}{\overline{p}}+\tau\frac{d}{dt}\left(\frac{p'}{\overline{p}}\right) \tag{1}$$

where

$$\tau=\frac{2\gamma}{3\gamma-1}\frac{V\overline{p}}{C_e^2\overline{\dot{m}}} \tag{2}$$

and $\overline{\dot{m}}$, $\overline{p}$ and $\overline{T}_e$ are the mean total flow rate through the combustor, mean pressure and exit temperature, respectively.

In the reported experiments, the actuator's control signal current and combustor pressure were recorded with LabView® sample and hold data acquisition system at 5000 samples per second. The mean and oscillating components, at the frequency of the LIA modulation, were obtained from the measured data using a previously developed ensemble averaging technique[6].

Open Loop Performance of the LIA Under Reactive Conditions

Figure 8 shows the spectra of the actuator's control signal current and combustor pressure oscillations obtained when the fuel flow rate was modulated at 860 Hz, the highest investigated frequency. Both spectra clearly exhibit a spike at the modulation frequency of 860 Hz, indicating that the control signal generated heat release oscillations within the combustor that excited pressure oscillations at the control signal's frequency. The pressure spectrum exhibits another, somewhat broader, spike at a frequency around 1450 Hz, corresponding to the frequency of the fundamental axial acoustic mode of the combustor. These fundamental mode oscillations were most likely excited by combustion and/or flow noise. It should be also noted that while the magnitudes of the spikes at 860 and 1450 Hz in Fig. 8 are approximately the same, the amount of energy required to drive each of these modes was quite different. The energy required to drive the combustor at 1450 Hz was small because this spike represents resonance operation of the system. In contrast, significant heat release oscillations were probably required to drive the pressure oscillations at the off resonance frequency of 860 Hz. The demonstration that modulation of the LIA's fuel injection rate produced heat release and pressure oscillations at off resonant operating conditions strongly suggest that such LIA could be used to generate significant heat release oscillations within unstable combustors that would damp the oscillations.

Figures 9 and 10 present comparisons of the frequency dependence of the phase delay and normalized gain measured in this study with a diesel fuel and corresponding data obtained in a previous study[6] with methane. The plotted phase delay is the phase difference between the actuator's control signal current and the corresponding heat release oscillations, and the normalized gain describes the gain normalized with respect to a reference gain measured at a frequency of 50 Hz; that is,

$$\textit{Normalized gain} \equiv \frac{\left|\textit{Heat release oscillations magnitude / Actuator current magnitude}\right|}{\left|\textit{Heat release oscillations magnitude / Actuator current magnitude}\right|_{@50\,Hz}}$$

Figure 9 shows that the phase delays produced by the LIA are significantly longer that those produced by the gaseous fuel actuator[6]. In the 0-400 Hz frequency range, the LIA produced phase delays that are nearly twice those associated with gaseous fuel. This result was expected as the combustion of liquid fuels require the additional steps of atomization and evaporation, when compared to the combustion of a gaseous fuel, which should increase the combustion process time delay. Also, the different trajectories of the fuel droplets would most likely affect the combustion process time delay in a manner that is currently not understood.

In contrast to the expected behavior of the phase delay, the behavior exhibited by the combustion process gain, see Fig. 10, was unexpected. Generally, one would expect that the attenuation of a process (i.e., heat release oscillations) would increase as the phase delay increases, resulting in lower gains at larger phase delays. Accordingly, the normalized gain produced by the LIA should have been smaller than that produced by the combustion of a gaseous fuel. The opposite behavior is exhibited by the data in Fig. 10 where it is shown that the gains measured with the liquid fuel are larger than those measured with the gaseous fuel. This finding is a significant, and should be further investigated. Such studies should determine the

range of operating conditions under which oscillatory combustion of liquid fuels produces larger gains and the reasons for this behavior. Attaining these goals should lead to the development of more effective ACS that utilize LIA similar to the one investigated in this study, as the loss of gain is one of the major limitations of fuel control authority.

Summary and Conclusions

This paper describes the design and performance of a LIA that was developed for active control of combustion instabilities with a liquid fuel or oxidizer. The LIA has three types of controls; a "slow" one that controls the mean liquid flow rate, a "medium" controller that modulates the LIA's flow rate at frequencies of unstable combustor oscillations; and a "fast" controller that disturbs the fuel flow rate at high frequencies to enhance spray atomization.

Cold flow studies with a diesel fuel have shown that maximum enhancement of spray atomization in the investigated LIA occurs at 2400 Hz. It was also shown that the high frequency modulation atomizes the liquid fuel at low flow rates for which atomization does not occur under steady operation. A study of the effect of 2400 Hz modulation upon the LIA's sprays characteristics have shown that the modulation generally reduces the spray's arithmetic and Sauter mean droplets diameters.

An open loop study of the characteristics of the oscillatory combustion process produced by modulating the LIA fuel injection rate over a 0-860 Hz frequency range has shown the following: 1. the LIA can generate significant heat release oscillations over the investigated frequency range, 2. the phase delays produced by the oscillatory combustion process of the diesel fuel are larger than those found in previous studies with methane, apparently due to the additional atomization and evaporation steps, and 3. contrary to expectations, the gain of the oscillatory diesel fuel combustion process was larger than that produced by the combustion of the methane, even though its associated time delay was larger.

Future studies under this program will focus on developing better understanding of the results obtained in the reported cold and "hot" flow studies, and the application of the developed LIA in closed loop control of combustion instabilities.

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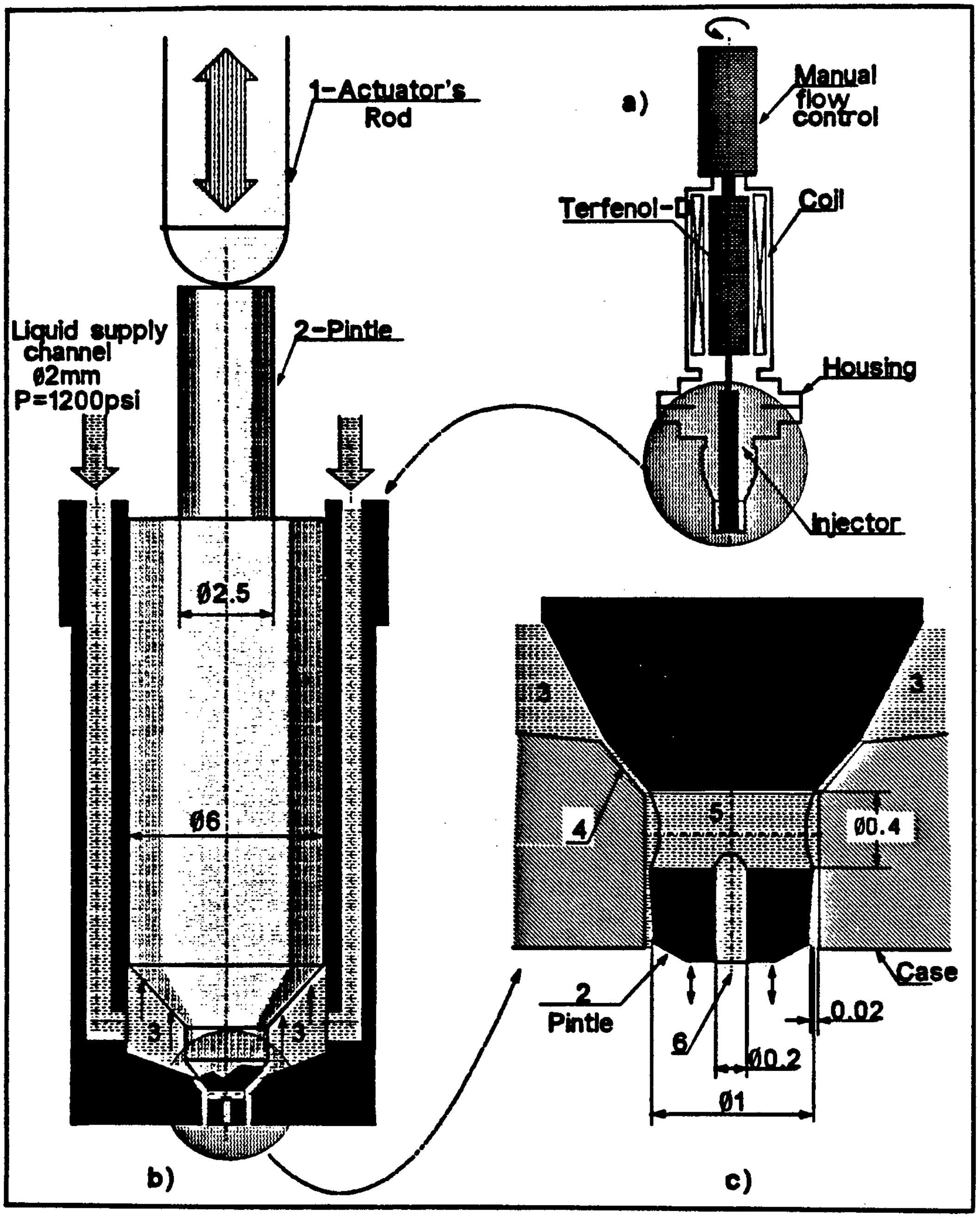


Figure 1. A schematic of the investigated liquid injector actuator (LIA).

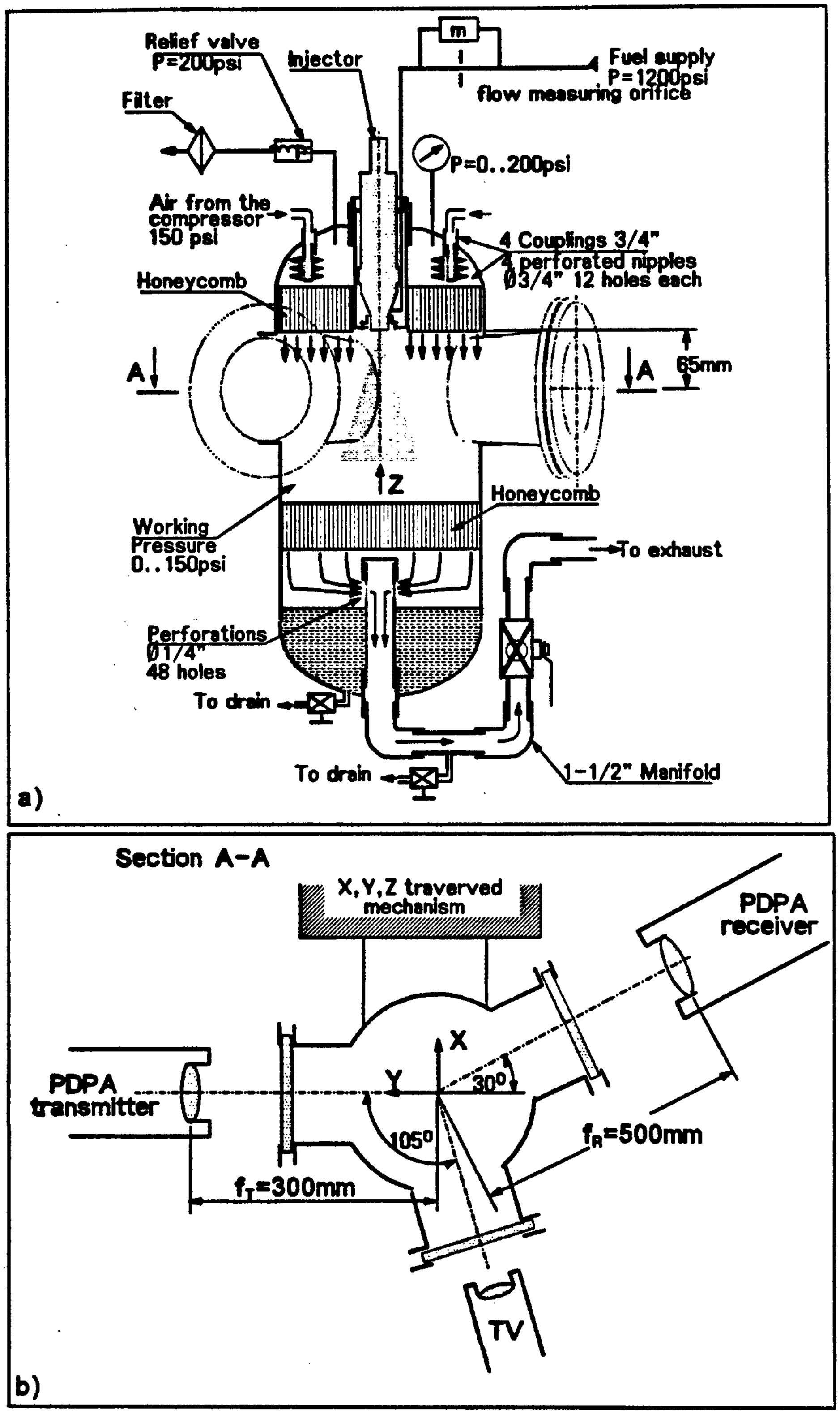


Figure 2. A schematic of the cold flow experimental setup.

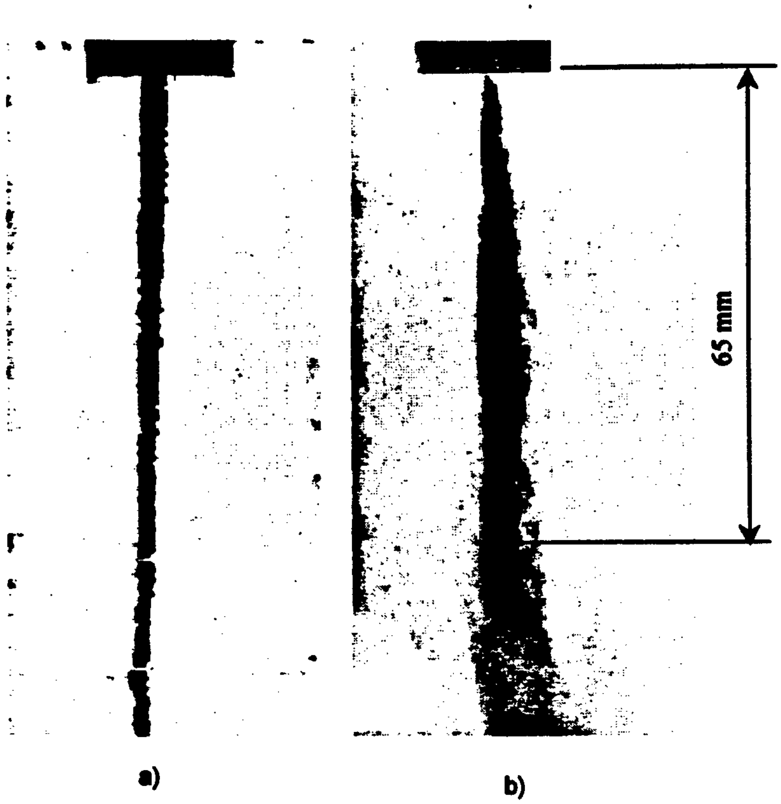
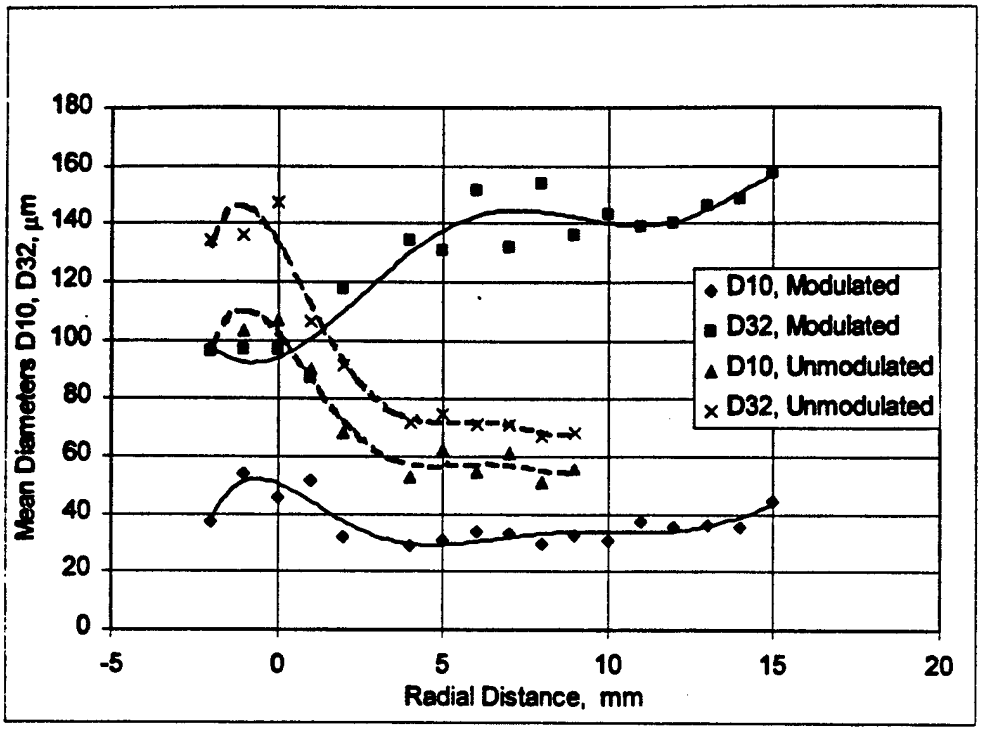
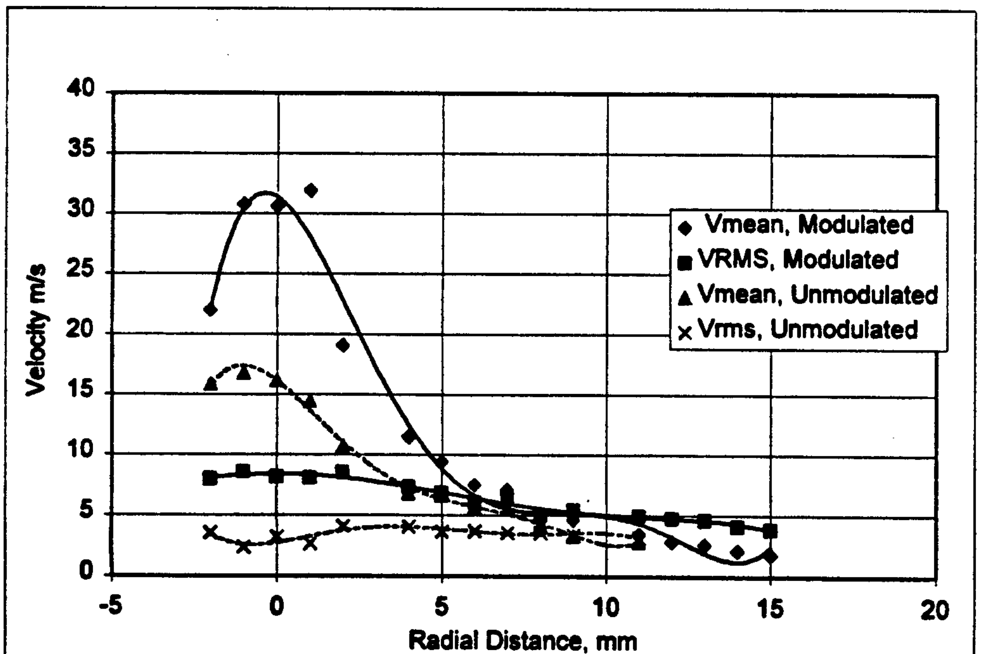


Figure 3. Photographs of 0.5 g/sec of diesel fuel emerging from the LIA under steady (a) and modulated (b) operating conditions.

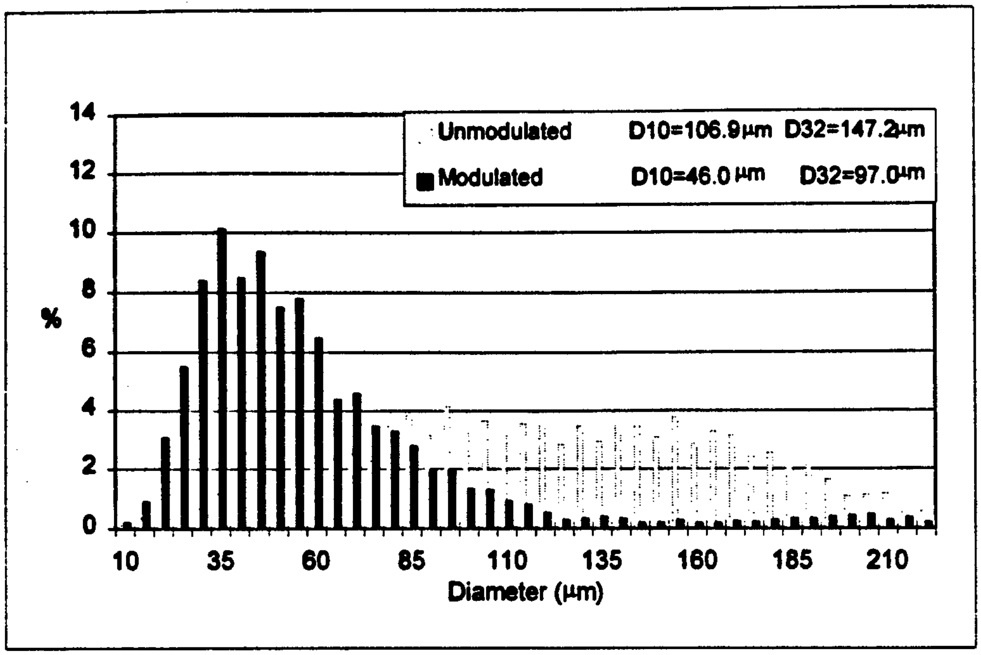


4-a

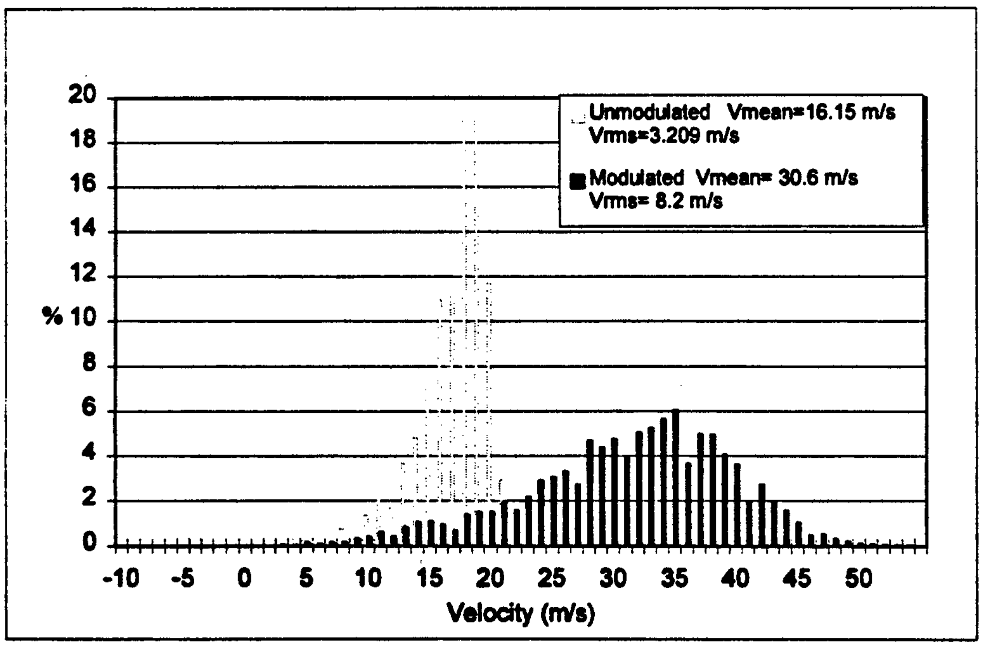


4-b

Figure 4. Effect of the modulation upon the spray characteristics obtained with a mean flow rate of 0.62 g/s, rms control signal amplitude of 0.3 Amp. and 2400 Hz modulation. Figs. 4-a, c show the effect upon the radial dependence and centerline histograms of the mean (D_{10}) and SMD (D_{32}) droplets diameters, respectively, while Figs. 4-b, d show the effect upon the radial dependence and centerline histograms of the mean and rms droplets velocities.

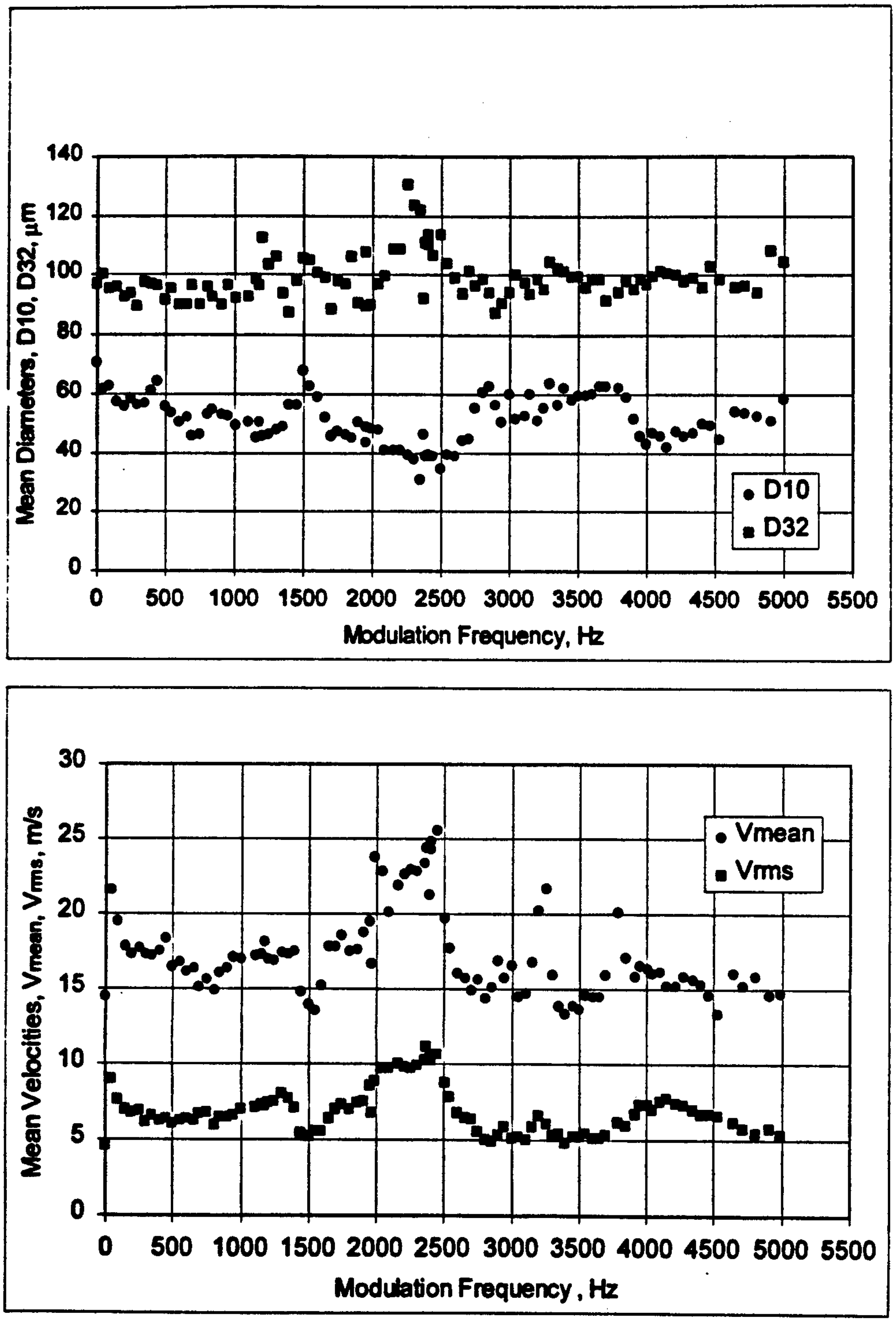


4-c



4-d

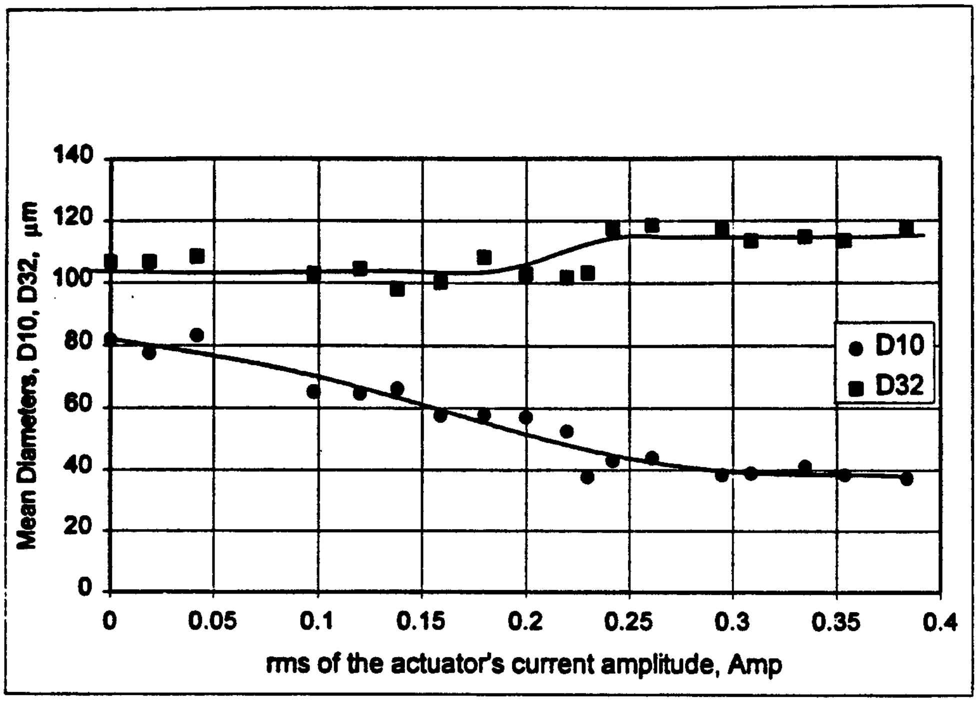
Figures 4-c,d



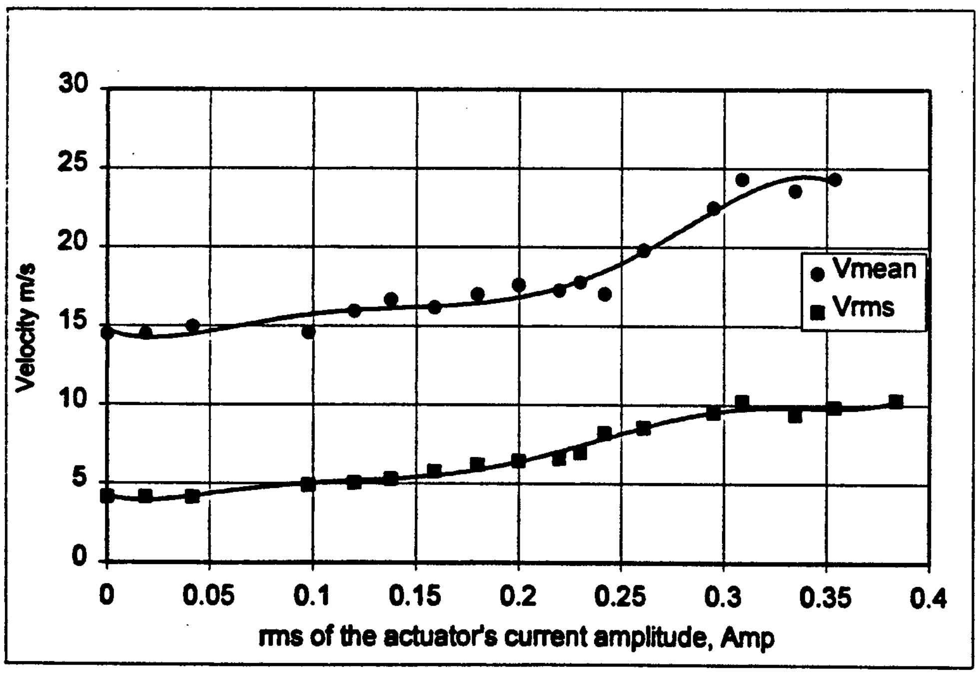
5-a

5-b

Figure 5. Frequency dependence of the mean (D_{10}) and SMD (D_{32}) diameters (a) and the mean (V_{mean}) and rms (V_{rms}) velocities (b) of the spray droplets measured 3 mm off the centerline with a constant control signal rms amplitude of 0.3 Amp. and a mean flow rate of 0.62 g/s.



6-a



6-b

Figure 6. Dependence of the mean and SMD diameters (a) and mean and rms velocities (b) of the spray droplets upon the rms amplitude of the control signal measured 3 mm off the centerline with a constant modulation frequency of 2400 Hz and a mean flow rate of 0.62 g/s.

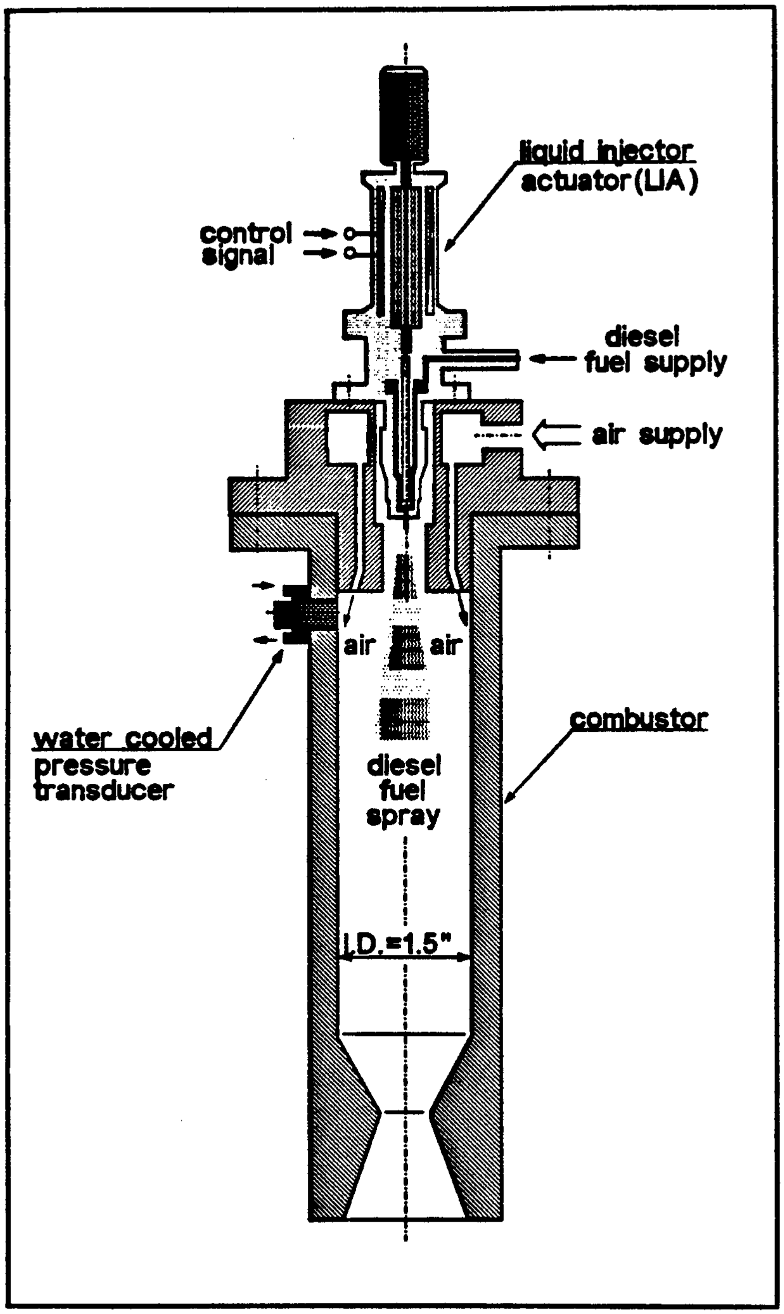


Figure 7. A schematic of the experimental setup used to investigate the characteristics of the heat release oscillations generated by the LIA.

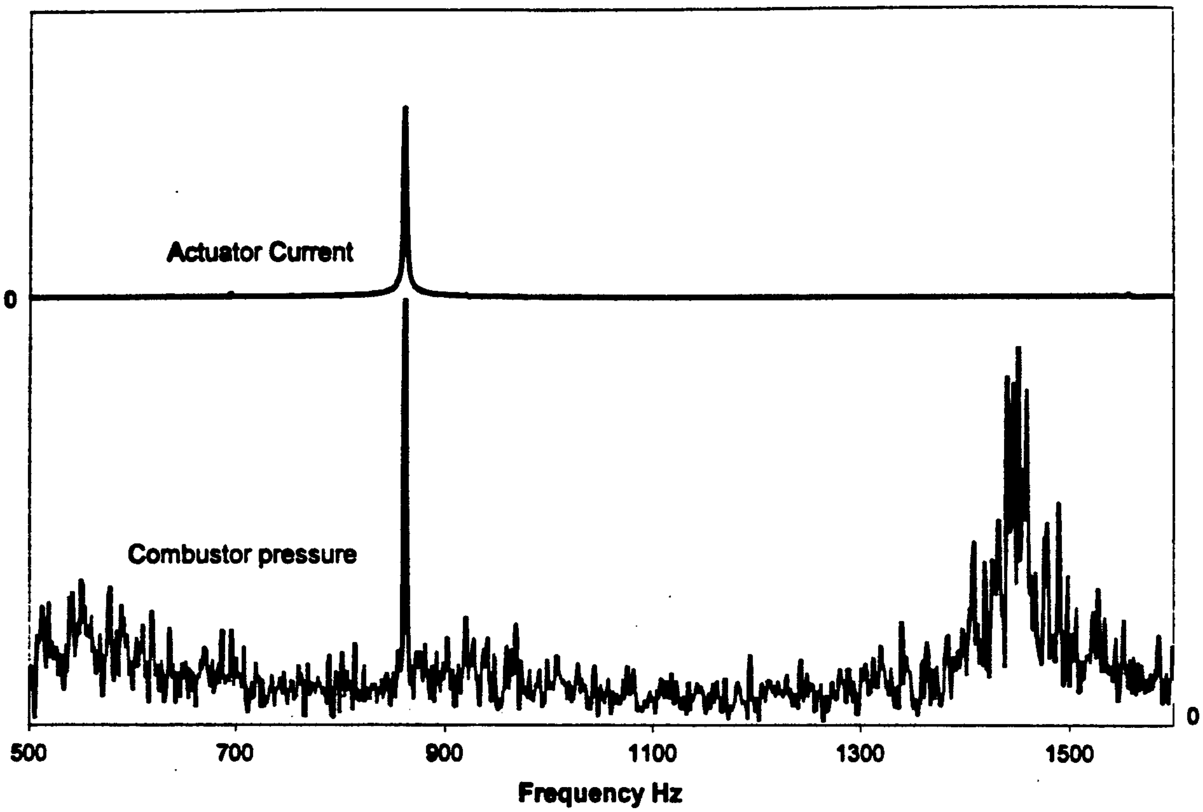


Figure 8. Frequency spectra of the actuator's control signal current and combustor pressure oscillations obtained with an 860 Hz modulation frequency

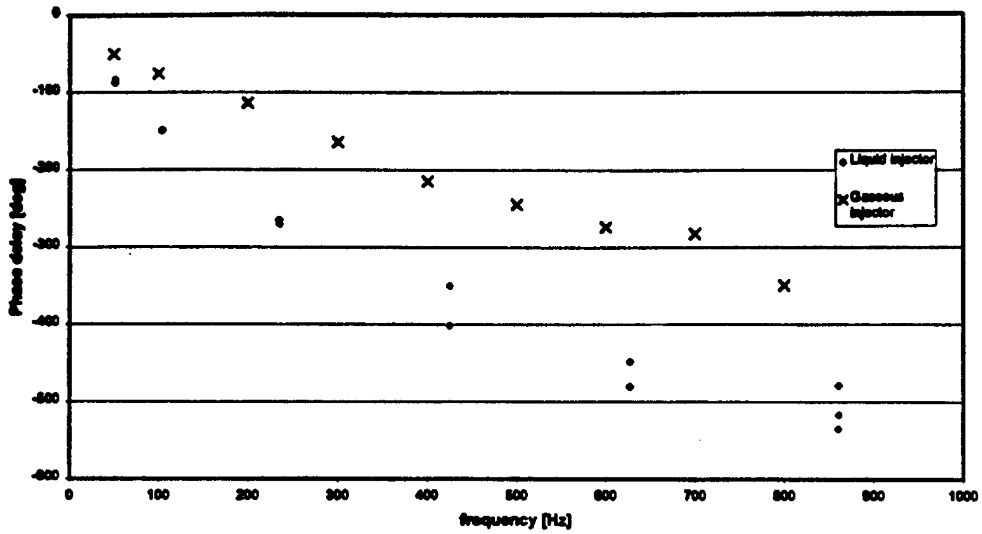


Figure 9. A comparison of the frequency dependence of the phase delay of the heat addition oscillations produced by the combustion of diesel fuel and methane.

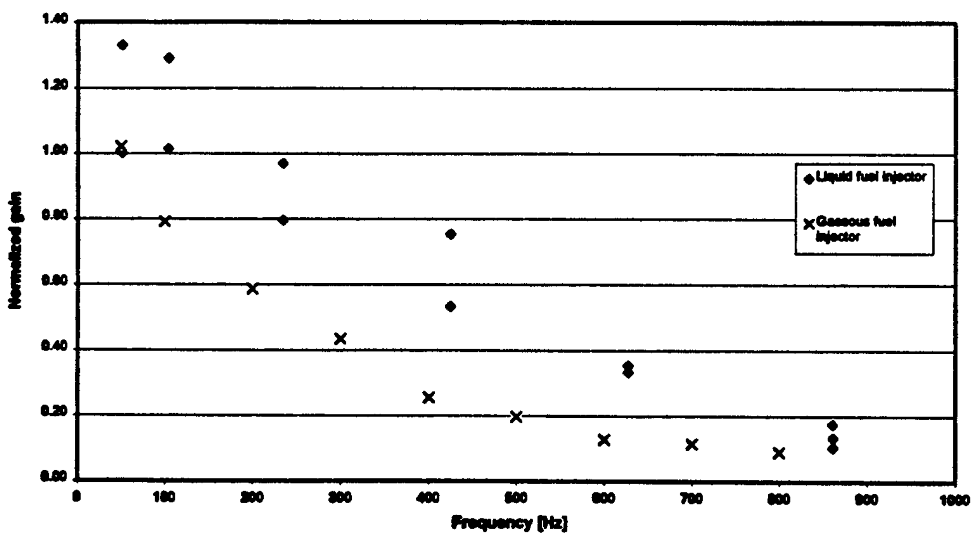


Figure 10. A comparison of the frequency dependence of the normalized gain of the heat addition oscillations produced by the combustion of diesel fuel and methane

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Experimental Characterization of an Oscillating Liquid Fuel Spray Combustion for Suppression of Combustion Instabilities

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Abstract

This paper describes the design performance and optimization of the control source which incorporates the liquid injector actuator (LIA) and flame holding system. It concentrates on the investigation of the oscillating flame characteristics which characterize it as an element of the control loop. Short flame length, deeply modulated amplitude profile and narrow phase domain provide the high effectiveness of the oscillating heat release. The performance of the control source was investigated mostly in reactive flow studies using a laboratory combustor with the extensive optical access to the reaction zone. Cold flow experiments using Phase Doppler Particle Analyzer for the measurements of the oscillating spray characteristics were used for the better understanding of the flame behavior. The hot flow studies determined the characteristics of the control flame over ranges of square wave modulation frequencies from 170 Hz to 800Hz and duty cycles from 20% to 80%.

The reactive flow studies have shown a good response of the flame to the fuel flow rate modulation in all investigated range of frequencies and duty cycles. High efficiency of the control source 70-80% was demonstrated in the 170-600Hz frequency range. This percentage reveals the part of modulated fuel which actually provides control. The cold flow studies determined the characteristics of the LIA spray, which influence the efficiency of control source. It was shown, that droplet's diameter and velocity distribution affect the amplitude profile, the phase domain, and the "pedestal" of oscillating flame. Spray characteristics can be optimized to match the requirements to the control flame. The most effective control flames were achieved when the cluster of fine droplets penetrated up to the center of the recirculation zone of the flame holder and then burns as a short flame burst as illustrated by a high speed photography.

Introduction

The most practical way to actively suppress combustion instabilities in aerospace combustors is by oscillating the injection of part of the liquid fuel to provide control of the heat release oscillations [1, 2]. Experimental studies show that, practically, 8-20% of the main fuel must be oscillated for the successful reduction of combustion instabilities [3, 4]. This means that several kilograms of fuel per second must injected in an

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* This Research was supported by AFOSR Contract No. F49620-96-1-0251 and funds provided by Georgia Tech; Dr. Mitat Bikan Contract Monitor.

oscillating manner to stabilize a practical combustor. This factor restrains the aerospace applications for active control of combustion instability by oscillating liquid fuel injection. Efforts to change the situation are concentrated on improving the external (in reference to combustor) elements of the control loop. These elements - sensors, observers and actuators were successfully developed recently [5, 6, 7]. In opposition to this approach, no attempts were made to optimize the injector/flame-holder assembly as an element of the control loop. From the point of combustion control, the requirements for this element are as follows:

- To provide the appropriate response in the required frequency range;
- To provide a compact flame with high combustion efficiency. The length of the reaction zone has to be negligible with respect to the combustor length (main mode wave length);
- The phase domain of the control flame oscillations (i.e. the phase variation along the length of combustor) must be minimized. Ideally, "uniform phase conditions" need to be achieved by optimization of the control source (see Fig.1a, b). Notice: shifting the entire phase domain to the optimum position for instability suppression is the responsibility of the external elements of the control loop (observer);
- The depth of the control flame modulation has to be maximized. The pedestal (i.e. pilot part of the control flame) does not take part in the suppression process (see Fig.1c). Fuel which provides pedestal is not available for control. Ideally, the control flame is ignited and exstinguished periodically at the frequency of modulation;

The main objective of this study is to optimize the liquid fuel control source, i.e. to provide the maximum control output by oscillating injection of the same amount of liquid fuel. The investigated control source represents a laboratory combustor with extensive optical access to the reaction zone. The combustor incorporates a liquid injector actuator (LIA) with a pintle type fuel injector [8] and a flame-holding system. Periodic modulation was applied to the liquid fuel flow stream by periodic movement of the pintle connected to the magnetostrictive actuator. Pintle movement, in turn, changed the pressure difference on the injector nozzle. The flame length, the width of the phase domain as well as the depth of the heat release modulation were taken as criteria for optimization. Optical diagnostics of the reacting and non reacting flows were used for characterization of the control source. CH* emissions from the narrow sections (slices) of the flame zone were used to determine of the longitudinal amplitude and phase profiles of the flame intensity oscillations. High-speed photography (up to 20 images per period of oscillations) was used to illustrate these profiles. A Phase Doppler Particle Analyzer (PDPA) was used to measure the oscillating spray characteristics to provide a better understanding of the oscillating flame behavior.

Experimental Technique

The Liquid Injector Actuator (LIA) [8] consists of a Terfenol D magnetostrictive actuator that is connected to a pintle-type injector, see figure 2. Time dependent control of the liquid flow rate through the LIA is obtained by changing the current to a coil that

surrounds the actuator. The control signal changes the coil's magnetic field, which, in turn, changes the length of the magnetostrictive rod. As the actuator's length changes, it pushes the pintle against a pressure force exerted by the liquid fuel that is supplied into the volume between the pintle's conical termination and the LIA's casing. The resulting force imbalance sets the pintle in motion. As the pintle moves backwards, the annular clearance between the two cones opens and allows liquid fuel to enter the nozzle. The pressure difference on the 200μm diameter nozzle changes as the width of the cross sectional area of the annular clearance changes. This pressure difference forces the liquid through the nozzle at the downstream end of the pintle where it emerges as a spray.

Model Combustor consists of an air distributor which is attached to LIA, a cone flameholder and a combustor wall, see Fig.2. The air devides the flow of air into two parts. 33% of the air is mixed with the liquid spray of the LIA using holes tangential to the spray pattern. The remaining air provides the annular air flow near the cone flame-holder. The maximum air supply is 15g/sec, and the maximum air temperature is 300^0C. Combustor wall is made of a quartz tube with a diameter of d_{in}=42mm and 2mm thickness. That enables optical access for measurements. Flameholding is achieved by the vortex system produced by the fuel & air jet extension at the exit of the cone and subsequent mixing with the annular secondary airflow. The modeling fuel is n-heptane (C_7H_{16}) with the maximum flow rate 1g/sec.

Measurements of the heat release response were based on the effect of the chemiluminescence of CH* radicals (λ=431.5nm). A special measurement instrument for scanning the oscillating flame was developed, see Fig.3. It incorporates a photomultiplier (PMT), a narrow band pass interference filter λ=430±5nm and an optical system. The CH* emission collected from a narrow section (slice) of the scanning flame zone through two 1.5x40mm slot apertures using a 50mm focal length lens (d=70mm) was focused through the filter onto the photo-multiplier. The distance between two apertures was 120mm, and the distance from the first aperture to the combustor was also 120mm. This design limited the photomultiplier's instantaneous line of sight to a 3mm thick section of the reaction zone. The instrument was mounted on the remotely controlled traverse support to provide a slowly moving PMT view zone along the combustor. A signal which characterized the instantaneous LIA pintle position was used as a reference to provide the post run phase calculations. Measurements of the pintle position were provided using a PHILTEC non-contact fiber optic displacement sensor, which is based upon detecting the intensity of reflected light. The actuator rod was equipped with a mirror for this purpose, as shown in Fig.2. The PMT signal, the pintle displacement signal as well as a voltage proportional to the instrument position were all sampled by the computerized data acquisition system using LabView software. The sampling rate and total scanning time were adjusted to achieve good quality FFT analysis of the entire reaction zone.

High speed photography was also used for reaction zone monitoring. The type of camera used was a Kodak ExtraPro Intensified imager camera, with a controllable shutter speed up to 4000Hz. The shutter was synchronized with the LIA's control signal through a frequency multiplier. To provide camera control TTL impulses, LIA's frequency was multiplied by 12-20. Flame emission was collected by the camera's optics through the narrow band pass interference filter λ=430±5nm (the same type as for PMT).

An "Aerometrics" Phase Doppler Particle Analyzer (PDPA) was used to characterize the sprays in cold flow experiments. During a test, cold air was injected through the combustor. Combustor is mounted on a traversing mechanism that can be precisely moved along three mutually perpendicular coordinates, thus providing capabilities for placing any point in the spray at the intersection of the PDPA's laser beams. Analysis of the PDPA data determines the arithmetic and Sauter mean diameters of the spray. Their definitions are given by

Sauter Mean Diameter = $D_{32} = \Sigma n_i d_i^3 / \Sigma n_i d_i^2$

Arithmetic Mean Diameter = $D_{10} = \Sigma n_i d_i / \Sigma n_i$

where n_i is the number of droplets in the size group *"i"*, which corresponds to the mean diameter d_i. Analysis of the PDPA data also determined the mean and RMS components of the spray droplets velocities at the measurement location

Experimental Results

This section describes and compares the characteristics of the oscillating control flame produced in the model combustor by the LIA with and without modulation of the liquid stream. The square wave frequency of modulation was varied from 170Hz to 800Hz. The duty cycle of the square wave control signal was varied from 20% to 80%. The percentage reflects the portion of time during the period of modulation that the pintle was in the upper position (see Fig.2 - injector fully or partially closed). All the tests were performed with n-heptane (C_7H_{16}) liquid fuel supplied at a pressure of 1200 psi. The average fuel-to-air ratio (FAR) of the combustor was maintained at 0.055 (fuel flow rate 0.55g/sec) in all reported experiments. Stoichiometric FAR of n-heptane with air is 0.066. Air temperature at the combustor intake was maintained at 100^0C.

Figures 4 and 5 show raw data profile of "modulated" and "steady" flames. Frequency of the control signal was 170Hz, duty cycle –50%. Both profiles clearly reveal variation of the intensity of the chemical reaction (notice: these profiles show the amplitude fluctuation vs. time as well as vs. distance from the flame holder). The reaction zone was demonstrated to be quite short (~80mm) for both cases. In the case of modulation, regular oscillations of the CH* emission at the frequency of the liquid stream modulation take place (Fig. 4b). The non-modulated profile reveals only wide band noise without any discernable regularity (Fig. 5b). The time history of the PMT signal (at the maximum intensity of the chemical reaction) as well as LIA pintle displacement sensor signal are shown on the Fig.6a.

Post run data processing based primarily on the Fast Furrier Transform (FFT) of acquired PMT and pintle displacement raw signals was done. The raw oscillating flame profile (as it shown in Fig.4a) was divided into 30-50 sections and each section was analyzed individually. The amplitude of the PMT signal corresponding to the frequency of liquid stream modulation as well as it's phase shift in reference to the pintle displacement sensor signal were determined for each section using the MATLAB SPECTRUM algorithm. The pedestal level of the reaction intensity (i.e. the non-oscillating part of PMT signal) was also determined for each section. The results were then compiled.

Profiles of amplitude, which characterize the magnitude of oscillations of the chemical reaction intensity, non-oscillating intensity levels (pedestal), as well as phase shift profiles are presented in Fig.7, 8 and 9 respectively. The graphs clearly demonstrate strong dependence of the amplitude, pedestal and phase shift profiles on the frequency and duty cycle of the control signal. Some data from Fig.7,8 and 9 are presented in the Table 1.

Table 1: Oscillating Flame Performances.

FREQUENCY, HZ	170		630	
DUTY CYCLE, %	20	80	20	80
Length of the Flame, mm	**50**	**150**	45	65
Phase Domain, degrees	**270**	**90**	280	165
Pedestal, %*	7	3.5	28	6

- Pedestal in this table was calculated as a portion of non-oscillating level to the entire level of CH emission intensity for the section, where the maximum oscillating intensity takes place.

This data demonstrates significant changes in the key parameters of the oscillating flame as a result of the control signal frequency and duty cycle variation. In particular, increasing the 170Hz modulation cycle "close" portion from 20% to 80% leads to an increase of the flame length as well as a decrease of the phase domain by factor of 3. The pedestal value decreased by factor of 2. At 630Hz modulation cycle, the strong influence of duty cycle on the pedestal level was revealed.

High speed photography of the oscillating flame provides a good illustration of these differences (see Fig.10 a,b,c). Pictures were taken at 25%, 50% and 75% duty cycle at the 170Hz frequency of liquid stream modulation. Twenty pictures were taken to characterize one period of flame oscillations (only 7 of each cycle are shown on the fig 10). Comparisons between these figures makes the shrinkage of the phase domain as well as pedestal decreasing as the "close" portion of cycle increases more understandable. In the case of "25% close", the flame is visible during the entire period of modulation. The flame is short and combustion occurs immediately near the flame holder. Only small variations of CH* emission intensity can be distinguished. When the LIA is "closed" during 50% of modulation cycle, the extinguishing of the flame takes place (the pedestal value is negligibly small). The flame became longer. Convection of the flame front along the combustor is clearly demonstrated. At "75% close" the extinguishing period became longer. The combustion process can be characterized as a burst or flash with it's center on the distance about 30mm from the flame holder.

Cold flow experiments were performed to explain this phenomena. Droplet size as well as droplet velocity distributions in the oscillating sprays measured 18mm from the flame holder for the frequency of modulation 170Hz are presented in figure 11. Comparison between the histograms of the droplet's size (Fig.11a) as well as the droplet's velocity (Fig.11b) reveals significant difference (see Table 2).

Table 2: Average parameters of the oscillating sprays.

FREQUENCY OF MODULATION, HZ	170		
DUTY CYCLE, %	25	50	75
Arithmetic Mean Diameter, D_{10}, μm	**39.1**	28.5	**18.5**
Sauter Mean Diameter, D_{32}, μm	116.8	100.7	105
Mean Velocity, m/sec	**8.78**	14.12	**25.89**
RMS Velocity, m/sec	8.4	11.57	17.7

As the "close" portion of the modulation cycle (injector is fully or partially closed) is increased from 25% to 75%, the mean velocity of the droplets is increased by factor of 3, and the arithmetic mean diameter of the droplets is decreased by factor 2. It is clear that these differences significantly change the penetration ability of the spray into the host flow near the flame holder as well as the time delay of the heat release, which relates mostly to the time of vaporization (i.e. droplet's diameters). This tendency is present for the investigated injector configuration as the frequency of modulation is increased up to 500Hz. At the frequencies of about 800Hz spray parameters are stabilized at the D_{10}=20-25μm and Vmean=5-7m/sec and do not depend any more on the "close" portion of the cycle of modulation.

Analysis

The operation of the investigated LIA can be understood by considering its design and the expected variations of the spray characteristics (i.e. droplet's size & velocity distribution). During a cycle of modulation the pintle (see Fig. 2) is moving from the partially or fully close position to the open position. The duty cycle of the control signal changes the time ratio between close and open pintle positions. As the duty cycle changes, the average flow rate through the injector has to remain constant, i.e. the fuel flow rate during the open portion of the cycle has to became smaller as the open time became larger. The only mechanism controlling fuel flow rate in the investigated injector configuration is changing the pressure difference on the nozzle. This is done by changing the pintle position. The pressure difference on the nozzle, in turn, changes the spray characteristics. This fact makes it possible to control the amplitude and phase profiles of the investigated oscillating flame as the fuel flowrate and the fuel-to-air ratio remain constant. The weakening of the duty cycle control effect on the oscillating flame characteristics at the frequencies higher then 600Hz is due to the time response of the actuator – amplifier configuration.

The opportunity to control the amplitude and phase characteristics of the oscillating flames made it possible to compare their effectiveness. The term effectiveness is used to describe the percentage of fuel burned that produced useful heat release oscillations. 100% effectiveness means that all the burned fuel produces oscillating heat release (i.e. no pedestal) with the zero phase distribution (all the sections of the flame oscillate in phase). It was assumed, that all the fuel injected was burned and the amount of CH* emission (which is proportional to the heat release) measured reflects how much fuel was injected. The calculation algorithm was as follows:

The ratio R_n between the oscillating and total heat release in each slice of the oscillating flame was calculated. The total heat release was determined by integration of

the raw PMT signal in time domain. To obtain the oscillating portion, the area under the pedestal was subtracted from the total heat release.

The Rayleigh criterion [9] was then incorporated by using the phase profiles. It was assumed that an electronic controller that could shift the phase profile of the heat release could be implemented (see Fig.1a). The theoretical controller would delay the LIA control signal in such a manner as to receive 180 degrees phase difference between the control heat release and pressure oscillations in the combustor. In this estimation the MATLAB algorithm located the flame slice which represents the center of the oscillating heat release profile, and then shifted the entire phase profile such that the phase corresponding to this point would be 180 degrees. The magnitude of driving or damping was then quantified by taking the projection of the ratio R_n between the oscillating and total heat release in each slice on the direction of the oscillating pressure vector (i.e. $E_n=R_n \cos \Psi_n$). So E_n represents the effectiveness of each slice.

Results of the slice effectiveness calculations for the frequencies of the modulation 170Hz and 630Hz with variation of duty cycles from 20% to 80% are summarized on the figure 12 as slice effectiveness vs. distance from the flame holder. Most of slices have negative E_n values (i.e., provide damping of the pressure oscillations). The numbers which characterize the entire oscillating flame effectiveness were calculated by summing of the E_n values corresponding to each slice ($E_\Sigma = -\Sigma E_n$) A negative sign was used here so as to receive a positive number for a final result. These data, which summarize the entire experimental series are shown on the figure 13. It is seen that the data demonstrates high effectiveness in controlling the investigated flames, especially in the frequency domain (170-600Hz), where the optimization of the spray characteristics by duty cycle variation can be successfully applied.

Summary and Conclusions

1. This paper describes the design and performance of the control source which incorporates the liquid injector actuator (LIA) and flame holding system. The performance of the control source was investigated mostly in reactive flow studies using a liquid fueled laboratory combustor with the extensive optical access to the reaction zone. Cold flow experiments using the Phase Doppler Particle Analizer for the measurements of the oscillating spray characteristics were performed to better understand the flame behavior. Hot flow studies determined the characteristics of the control flame over ranges of square wave modulation frequencies from 170 Hz to 800Hz and duty cycles from 20% to 80%.
2. The reactive flow studies have shown a good response of the flame to the fuel flow rate modulation in all investigated range of frequencies and duty cycles. High efficiency of the control source 70-80% was demonstrated in the 170-600Hz frequency range. It was shown that the oscillating flame characteristics can be successfully optimized to achieve maximum effectiveness by variation of the ratio between the "close" and "open" portion of the square wave modulation cycle.
3. The cold flow studies determined the characteristics of the LIA spray, which influence the efficiency of control source. Droplet size and penetration ability determine especially a region in the wake of flame holder where combustion takes place. This in

turn varies the amplitude profile and phase domain as well as the "pedestal" of the oscillating flame.

4. The most effective control flames were achieved when a cluster of fine droplets penetrated up to the center of the recirculation zone in the wake of flame holder and then burns as a brief flame burst as illustrated by high speed filming.

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Figure Captions

Fig.1. Estimation of the Oscillating Flame as an Element of the Control Loop for Suppression of Combustion Instability;

a) Vector diagram of the oscillating heat release.

Designations: $\Psi_{obs.}$ – Phase shifting by external observer (controller);
$\Delta\Psi$ – Phase domain of the control heat release;
$\Psi_{n.}$ – Phase shift of the heat release oscillations in the *n*-th slice;

b) Loss of the effectiveness of the oscillating control heat release due to large the phase domain.

c). Loss of the effectiveness of the oscillating control heat release because of enlarge of the pedestal.

Fig.2. Scheme of the Model Combustor.

Fig.3. Scheme of the Experimental Test Rig.

Fig.4. Intensity of CH* Emission from the 170Hz Modulated flame;

a) CH* Emission Intensity vs. Distance from the Flame-holder;
b) Power Spectrum of CH* Emission in the Section 23mm from the Flame-holder;

Fig. 5. Intensity of CH* Emission from the Unmodulated Flame;

a) CH* Emission Intensity vs. Distance from the Flameholder;
b) Power Spectrum of CH* Emission in the Section 23mm from the Flame-holder;

Fig.6. Raw PMT and Pintle Displacement Signals Taken in the Section of the 170Hz Modulated Flame 23mm from the Flame-holder;

a) Time History of the PMT and Pintle Displacement;
b) Power Spectrum of the Pintle Displacement Signal.

Fig.7. Magnitude of Oscillations of the Chemical Reaction Intensity vs. Distance from the Flame-holder;

a) Frequency of Square Wave Modulation 170Hz;
b) Frequency of Square Wave Modulation 630Hz.

Fig. 8. Non-oscillating Chemical Reaction Intensity (pedestal) vs. Distance from the Flame-holder;

a) Frequency of Square Wave Modulation 170Hz;
b) Frequency of Square Wave Modulation 630Hz.

Fig. 9. Phase Shift of the CH* Emission Oscillations vs. Distance from the Flame-holder (notice: the pintle displacement signal was taken as a reference for phase measurements);

a) Frequency of Square Wave Modulation 170Hz;
b) Frequency of Square Wave Modulation 630Hz.

Fig.10. High Speed Photography of the Oscillating Flame. Frequency of the square wave Modulation –170Hz.
a) Duty cycle = 25% (the percentage reflects the portion of time during the period of modulation when injector is closed);
b) Duty cycle = 50;
c) Duty cycle = 75%

Fig. 11. The Effect of Duty Cycle on Modulated Spray Characteristics. Cold flow Results: measurements were taken 18mm from the flame-holder on the spray centerline with 170Hz square wave modulation;
a) Droplet size distribution;
b) Droplet velocity distribution;

Fig.12. Local Effectiveness of the Control Flames vs. Distance from the Flame-holder;
a) 170Hz Square Wave Modulation;
b) 630 Hz Square Wave Modulation.

Fig.13. The Influence of Frequency of Square wave Modulation and Duty Cycle on the Entire Effectiveness of the Control Flames.

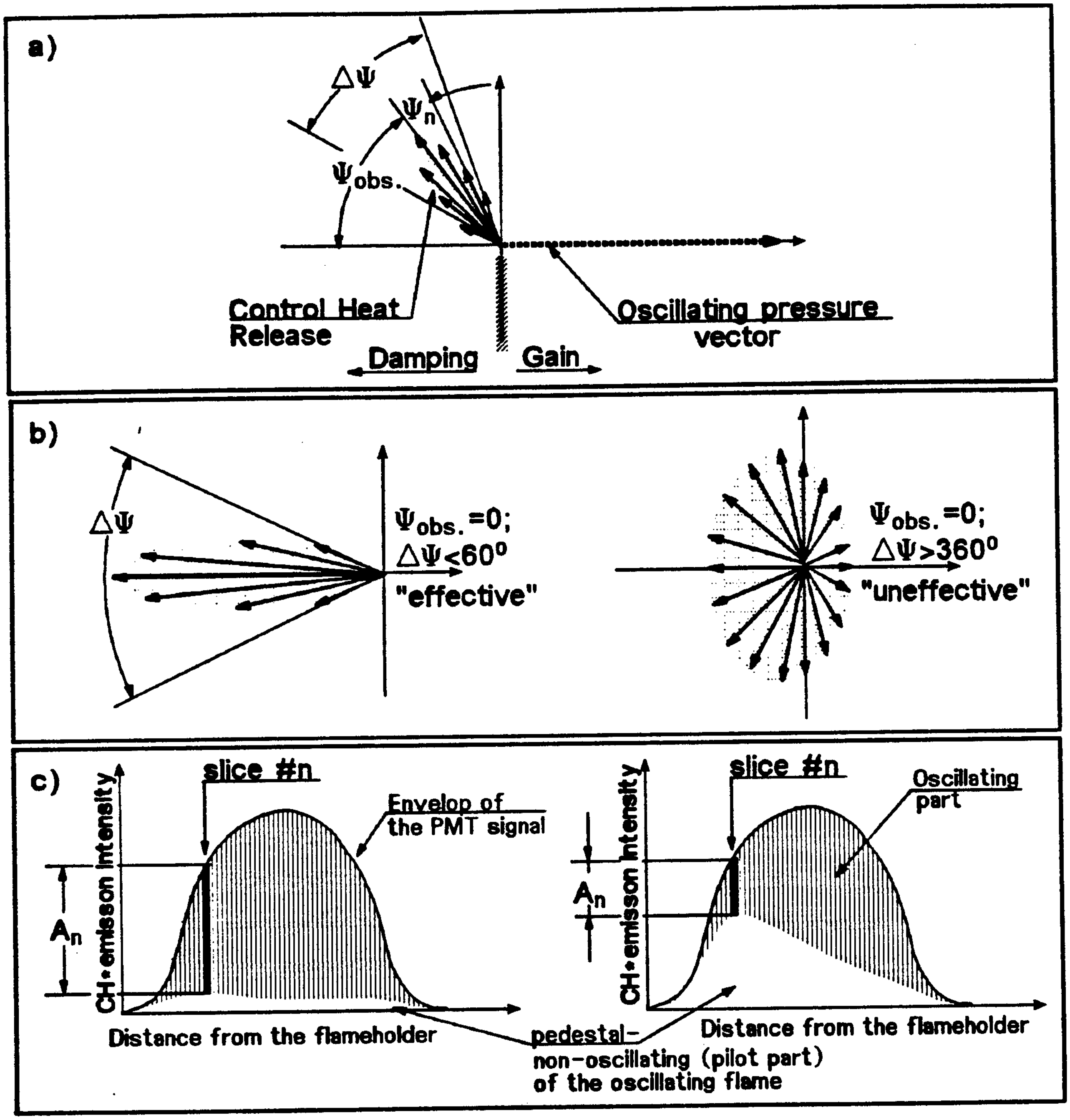


Fig.1. Estimation of the oscillating flame as an element of the control loop for suppression of combustion instability;

a) Vector diagram of the oscillating heat release.

Designations: $\Psi_{obs.}$ – Phase shifting by external observer (controller);
$\Delta\Psi$ – Phase domain of the control heat release;
$\Psi_{n.}$ – Phase shift of the heat release oscillations in the *n*-th slice;

b) Loss of the effectiveness of the oscillating control heat release due to large the phase domain.

c). Loss of the effectiveness of the oscillating control heat release because of enlarge of the pedestal.

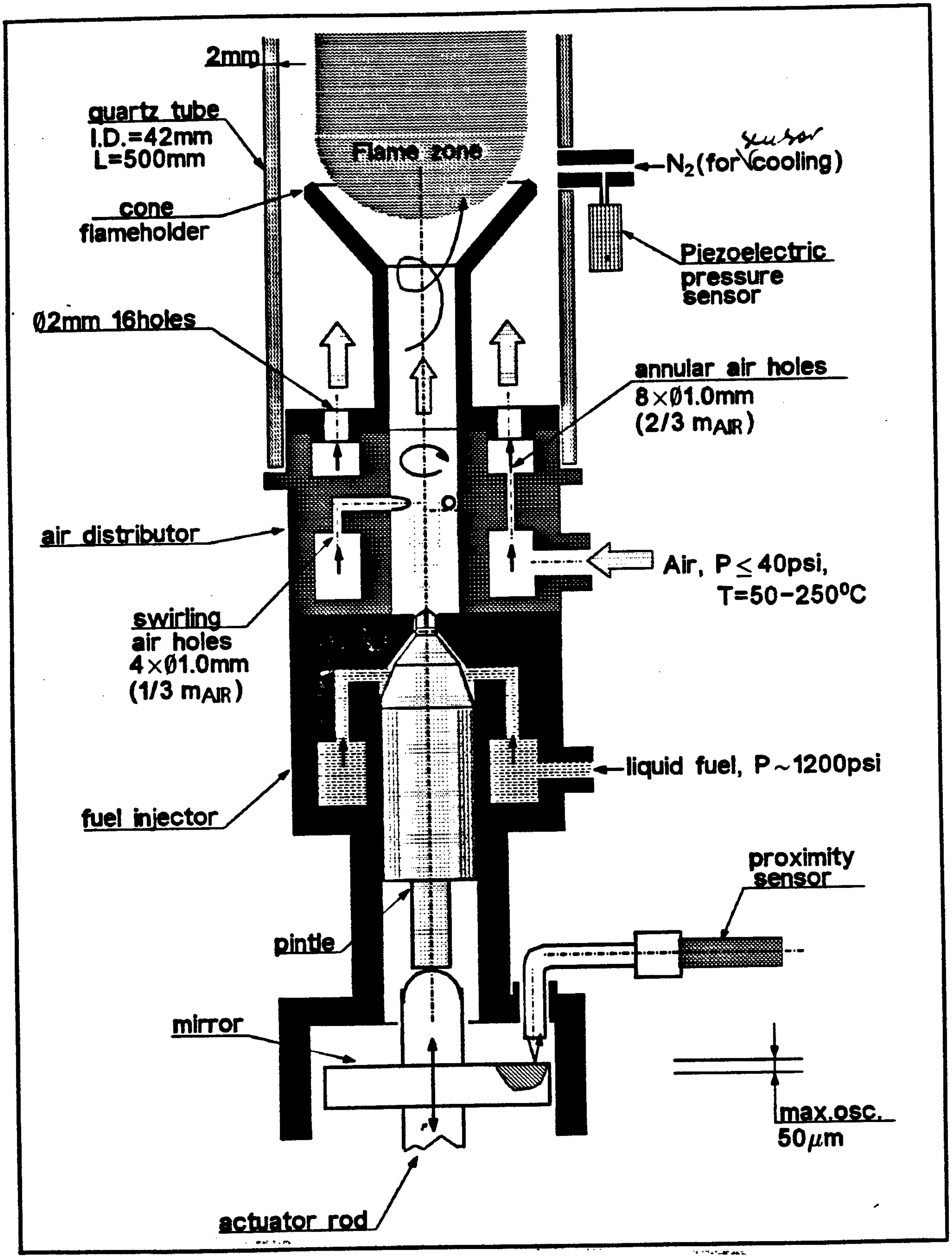


Fig.2. Scheme of the model combustor.

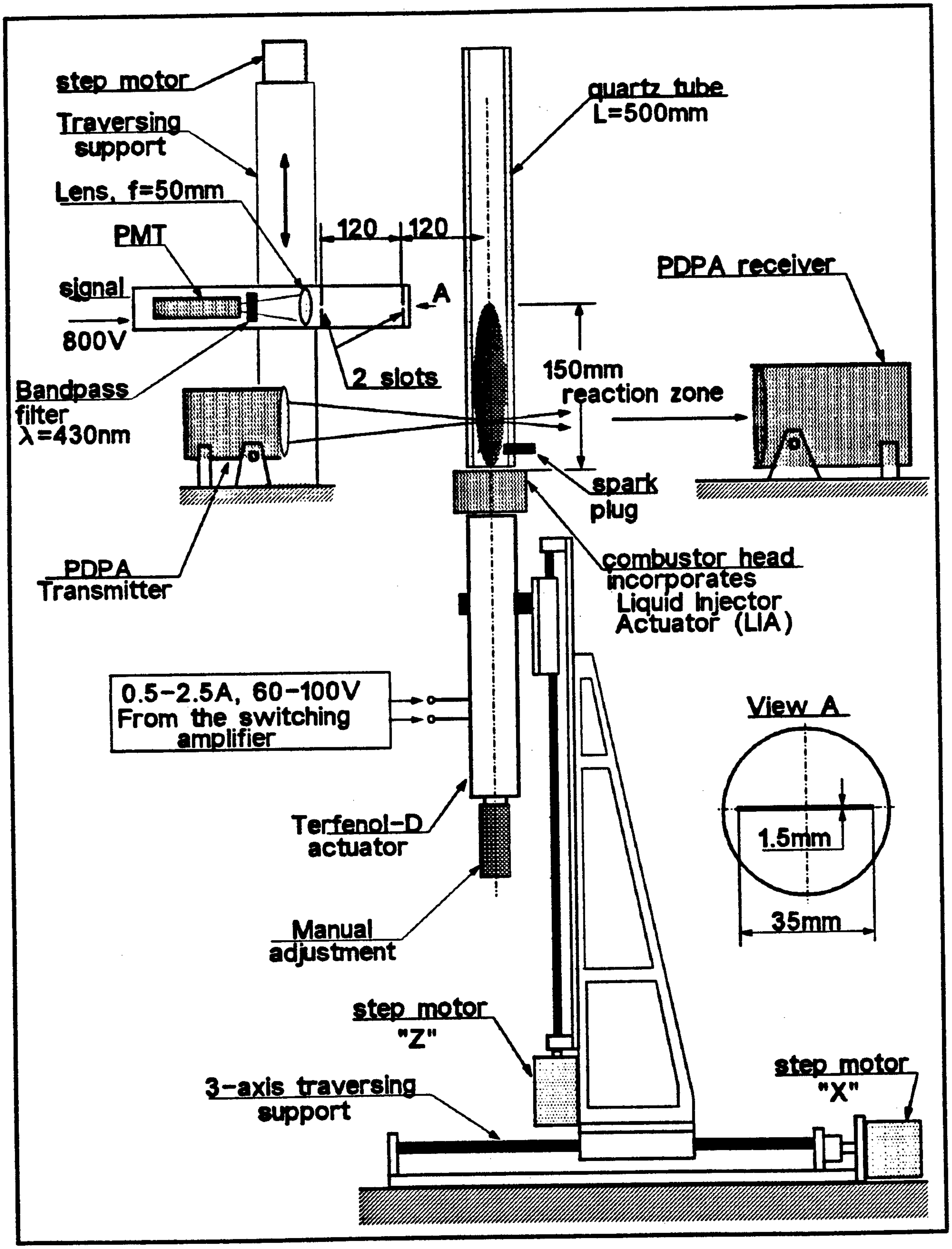
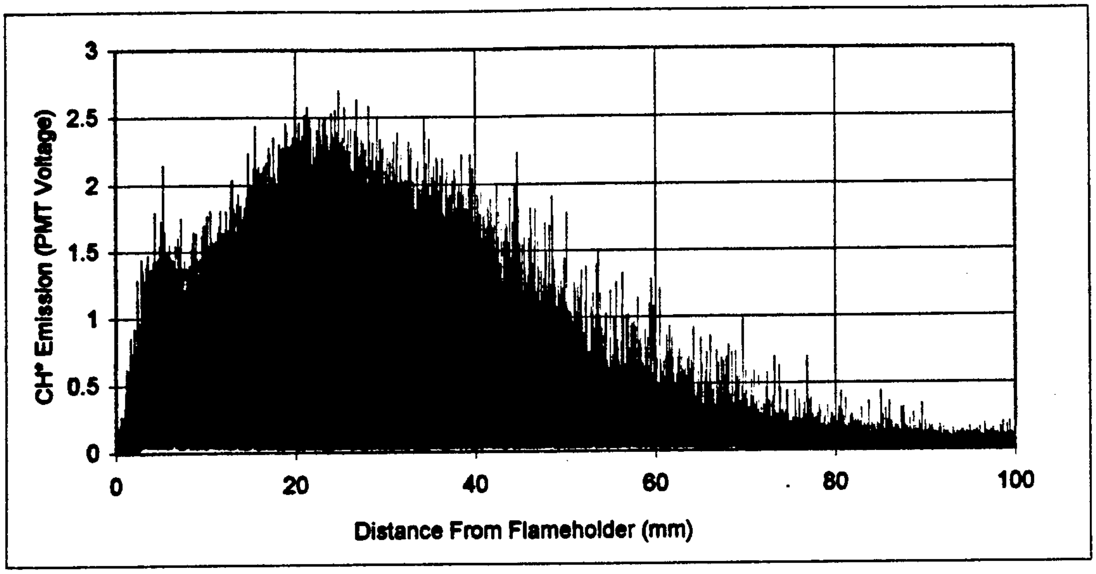


Fig.3. Scheme of the experimental test rig.



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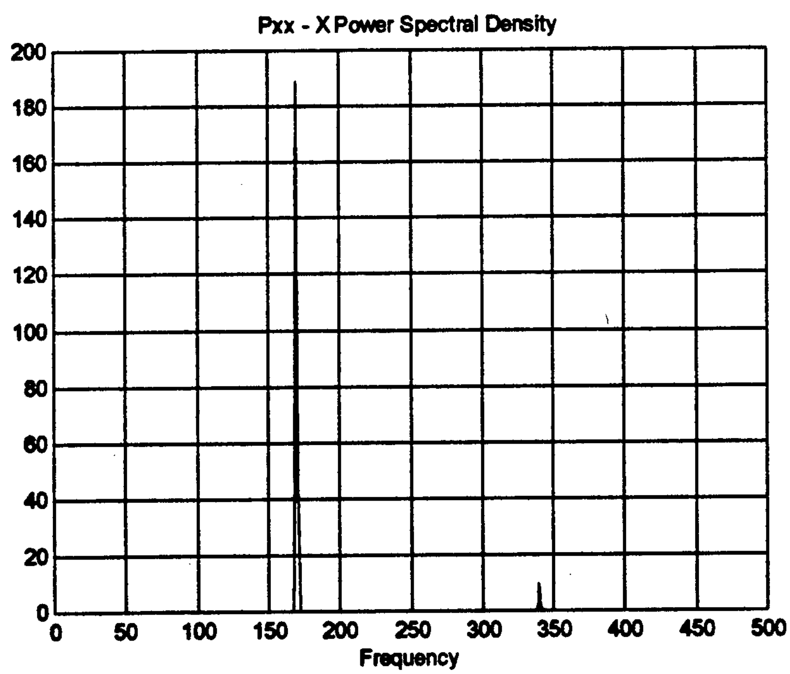
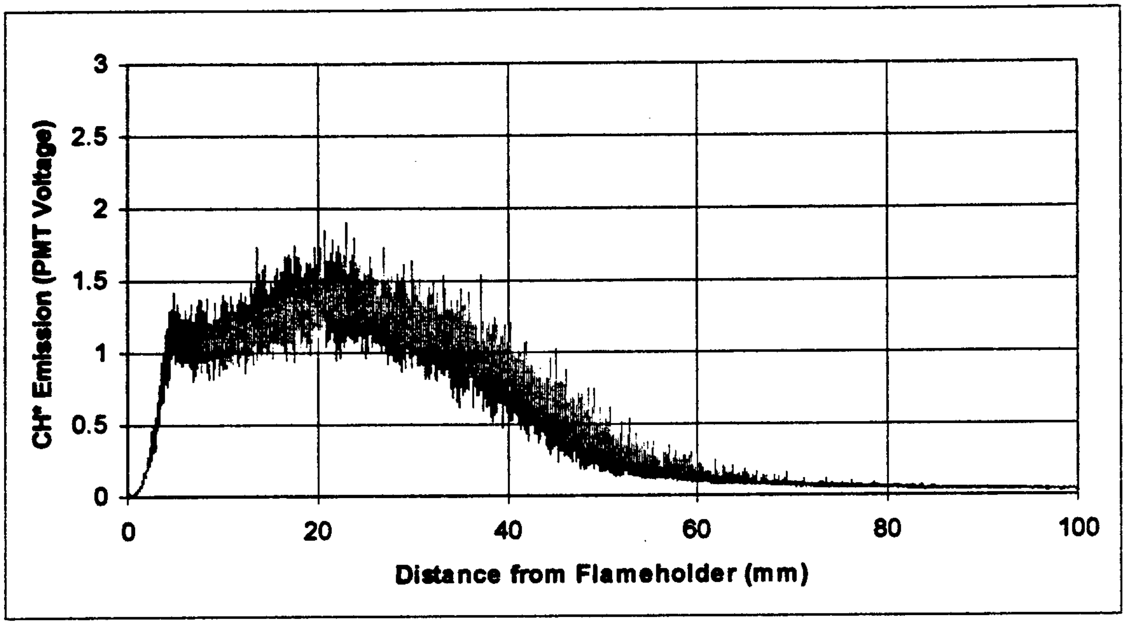


b)

Figure 4: Intensity of CH* Emission from the 170 Hz Modulated Flame

a) CH* Emission Intensity vs. Distance from the Flame-holder
b) Power Spectrum of the CH* Emission in the Section 23 mm from the flame-holder



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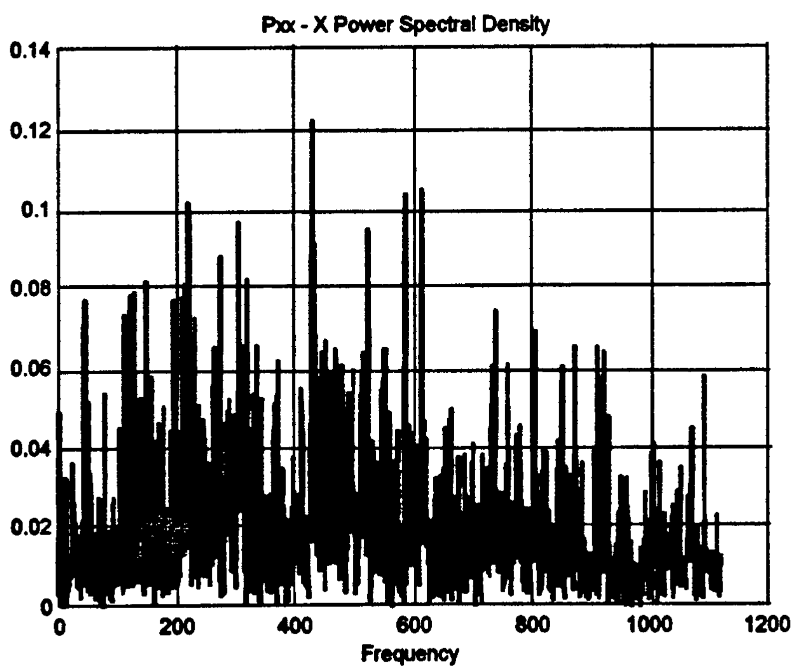

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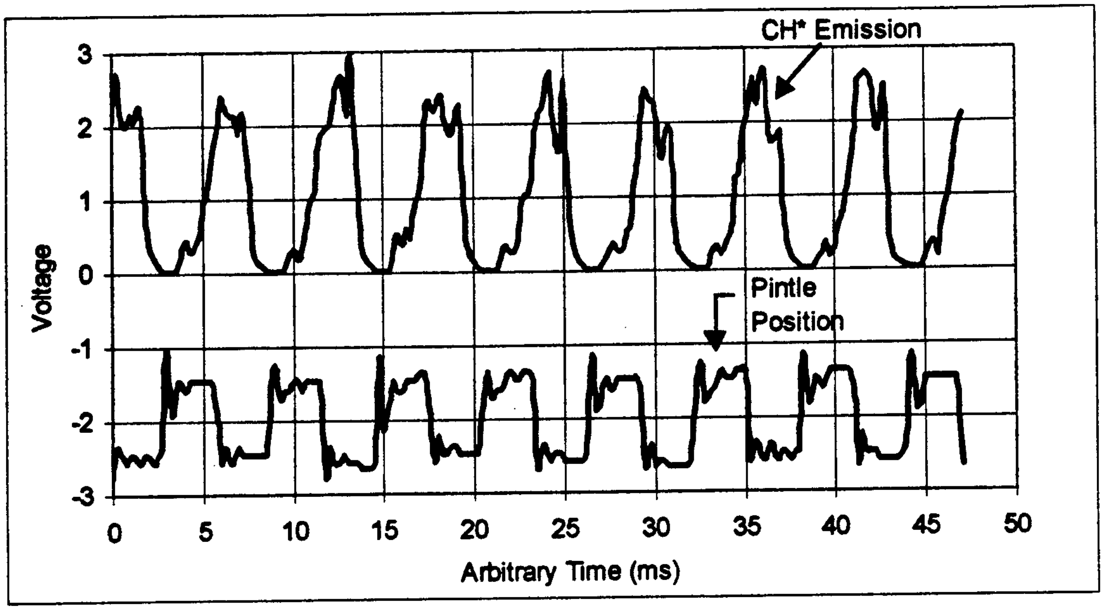
Figure 5: Intensity of CH* Emission from the Unmodulated Flame

a) CH* Emission Intensity vs. Distance from the Flame-holder
b) Power Spectrum of CH* Emission in the Section 23 mm from the Flame-holder



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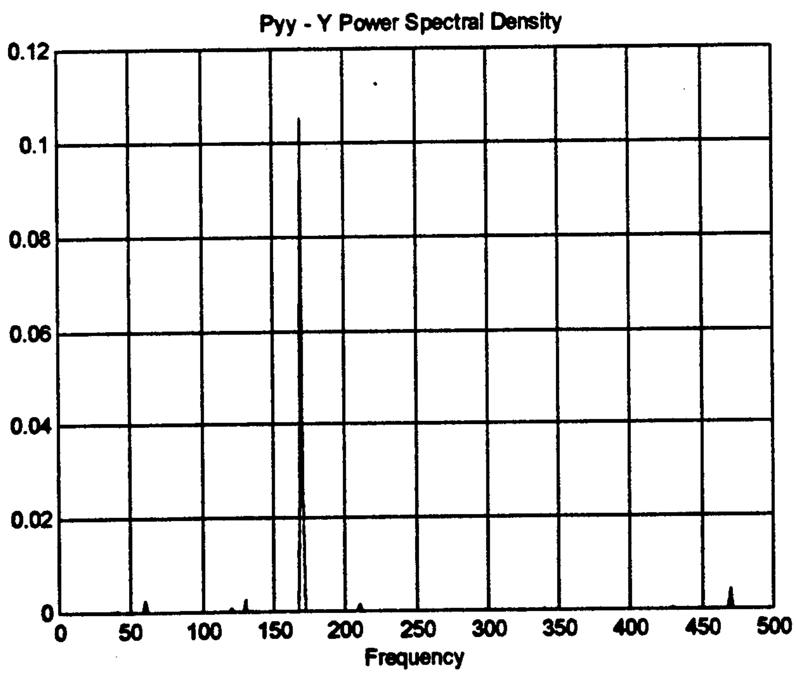
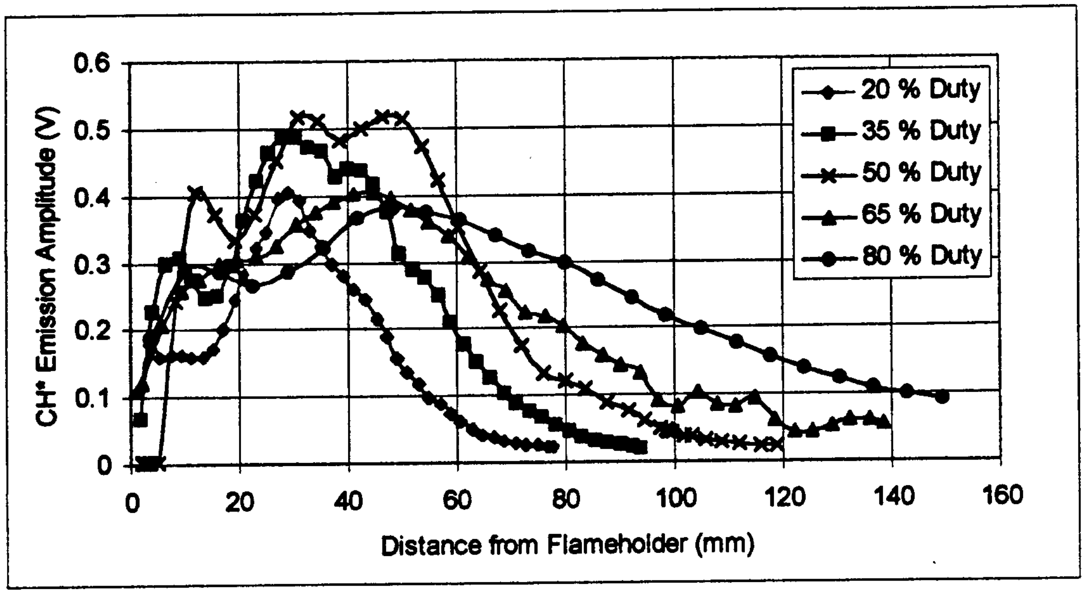


b)

Figure 6: Raw PMT and Pintle Displacement Signal taken in the Section 23 mm from the Flame-holder for the 170 Hz Modulated Flame

a) Time History of the PMT and Pintle Displacement
b) Power Spectrum of the Pintle Displacement Signal



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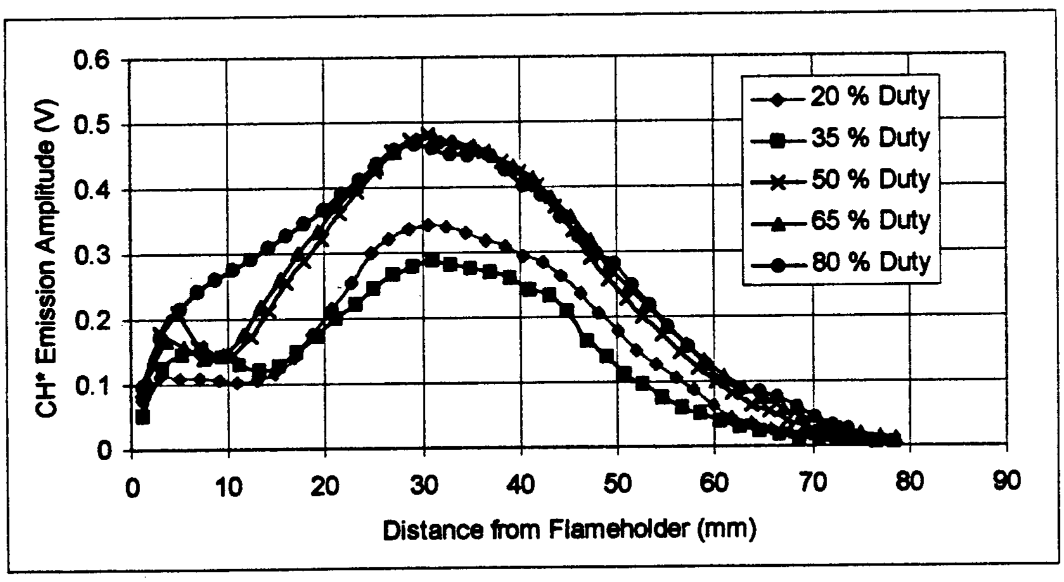

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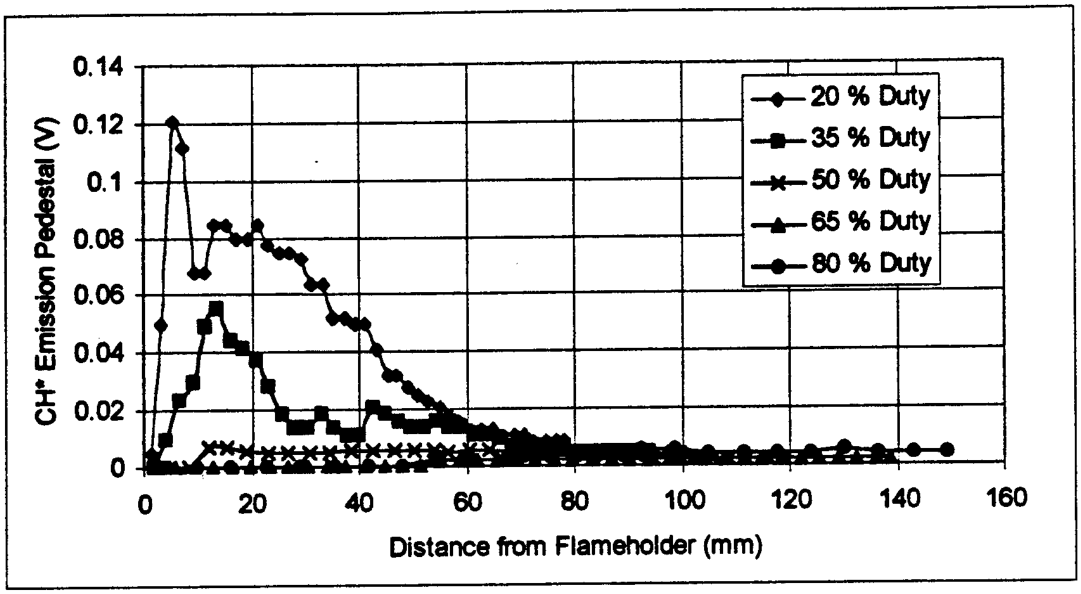
Figure 7: Magnitude of Oscillations of the Chemical Reaction Intensity vs. Distance from the Flame-holder

a) 170 Hz Square Wave Modulation
b) 630 Hz Square Wave Modulation



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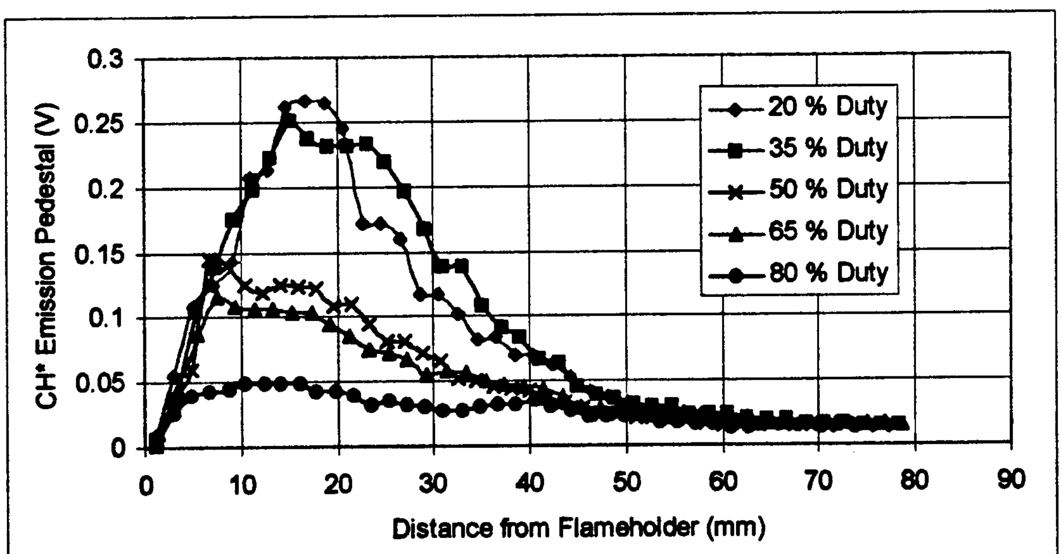

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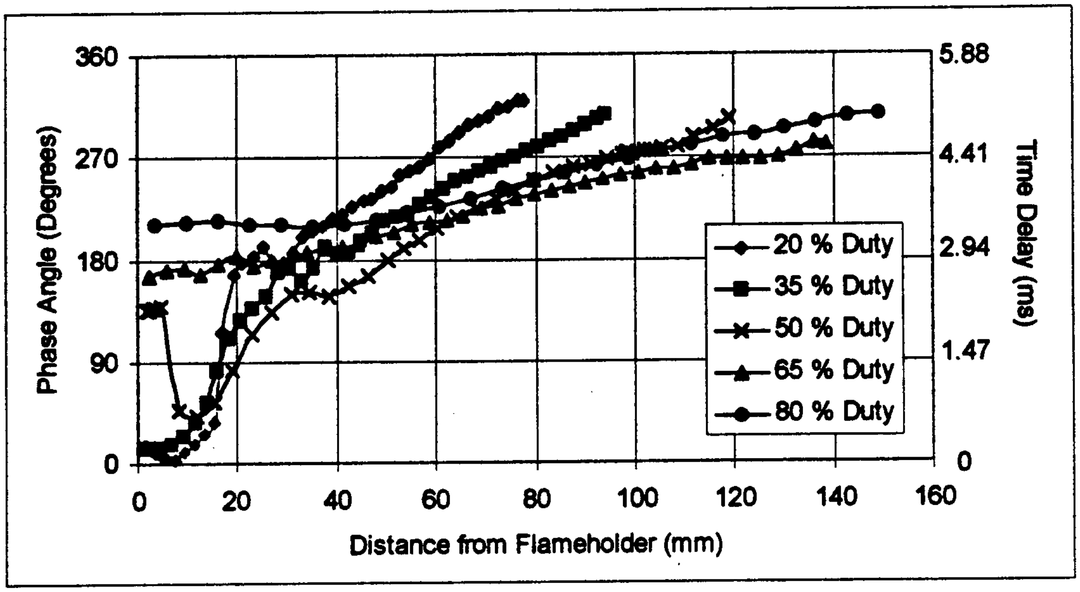
Figure 8: Non-oscillating Chemical Reaction Intensity (Pedestal) vs. Distance from the Flame-holder

a) 170 Hz Square Wave Modulation
b) 630 Hz Square Wave Modulation



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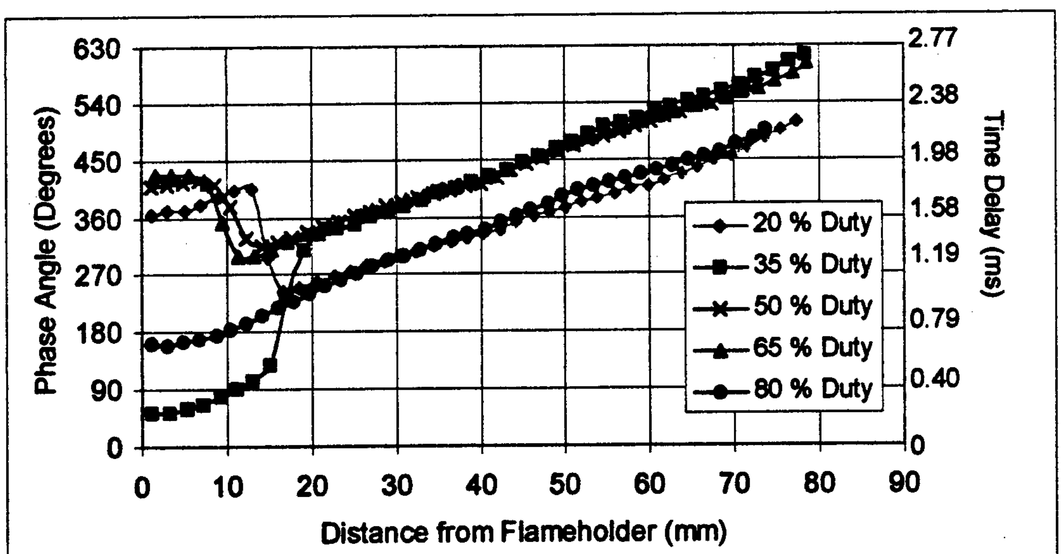

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Figure 9: Phase Shift of the CH* Emission Oscillations vs. Distance from the Flame-holder (notice: the pintle displacement signal was taken as a reference for phase measurements)

a) 170 Hz Square Wave Modulation
b) 630 Hz Square Wave Modulation

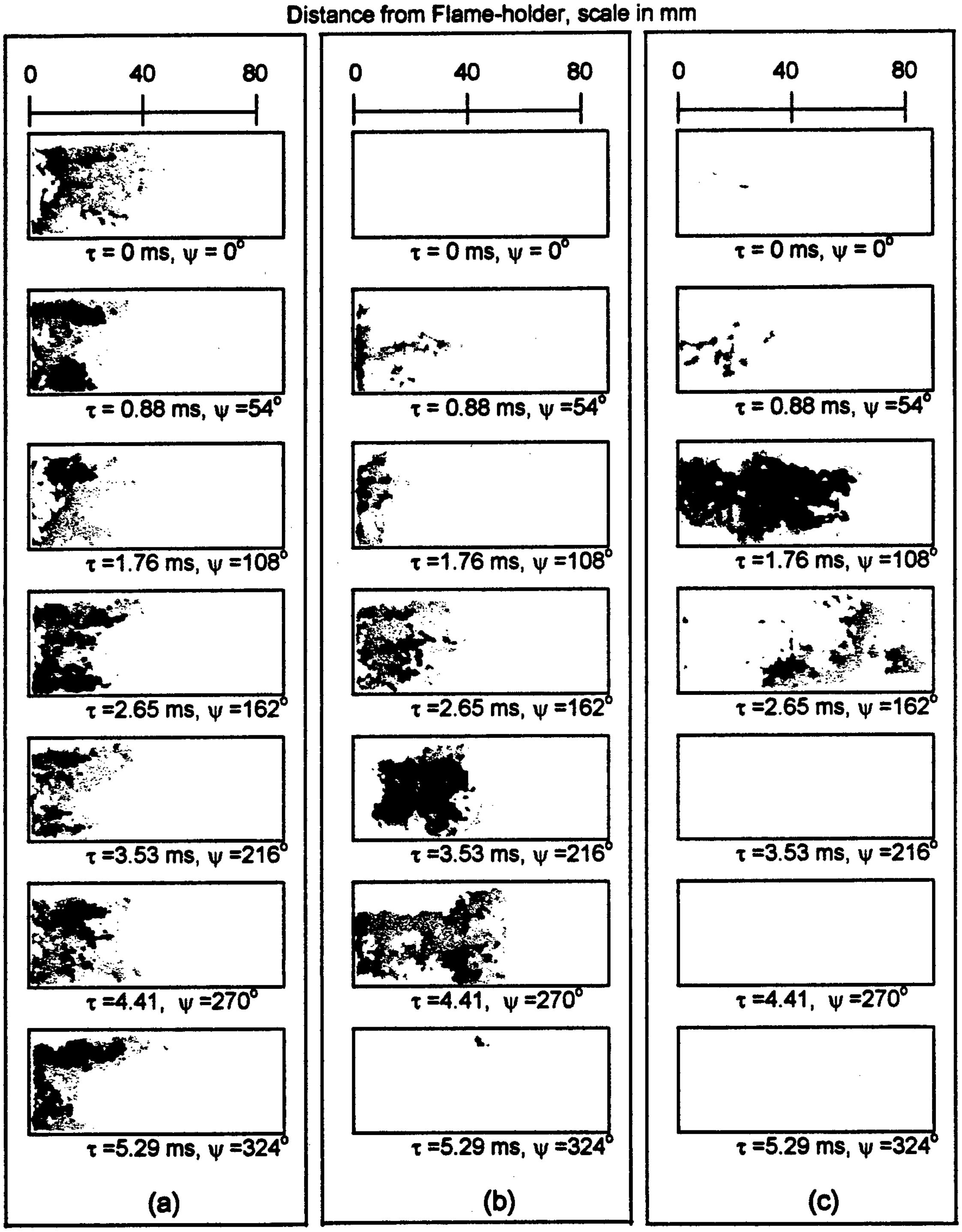
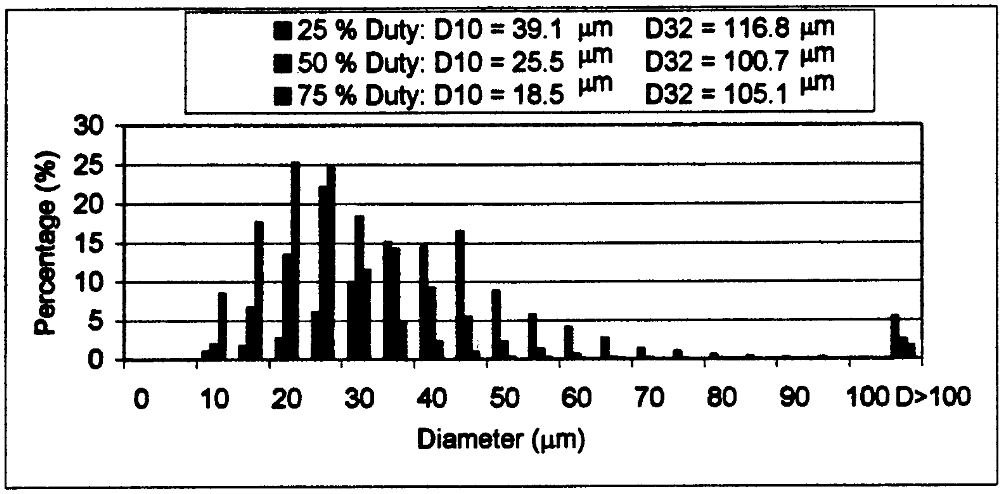
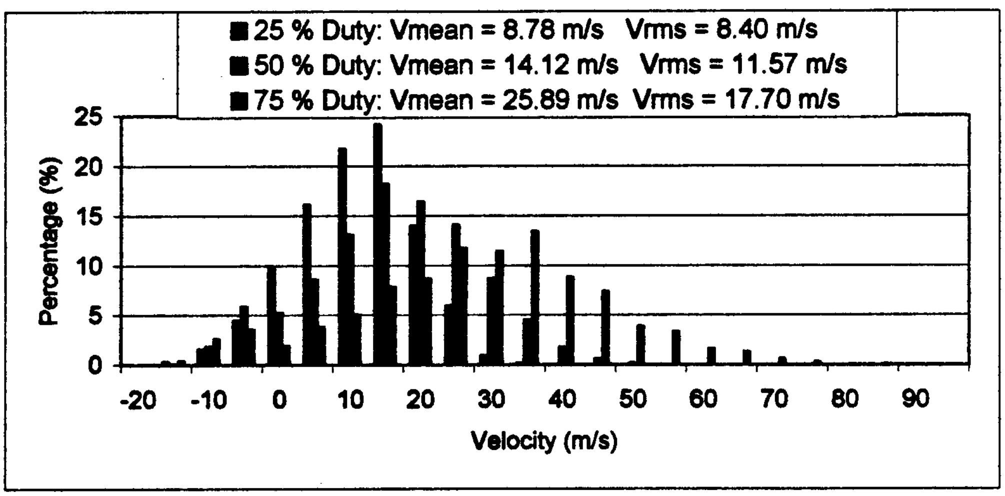


Figure 10: High-speed Photography of the Oscillating Flame for 170 Hz, Square Wave Modulation at Three Different Duty Cycles. (The percentage reflects the potion of time during the period of modulation when the injector is closed)

a) 25 % Duty Cycle
b) 50 % Duty Cycle
c) 75 % Duty Cycle



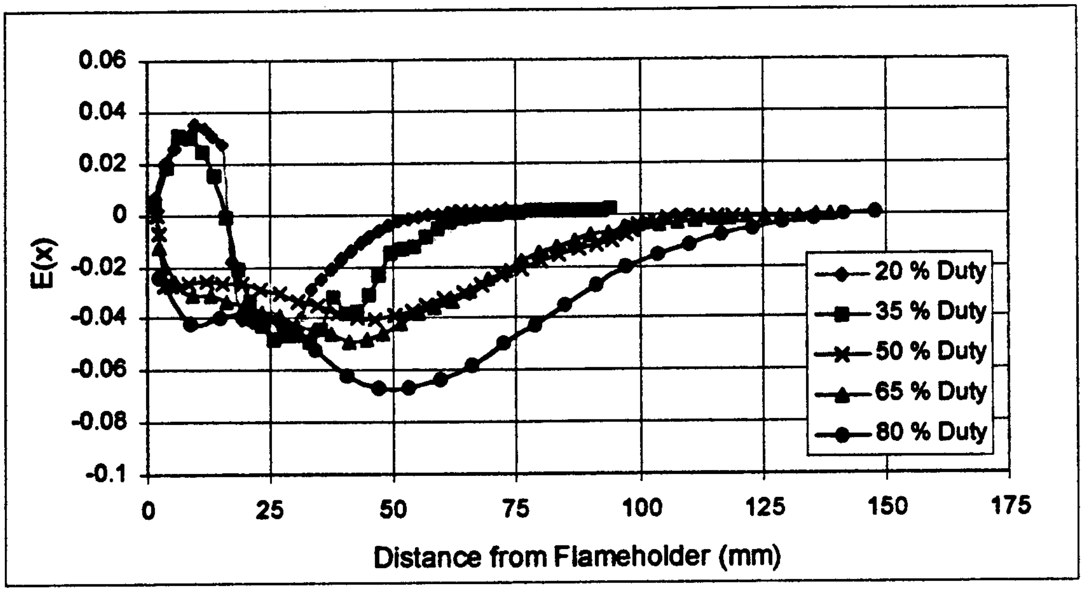
a)



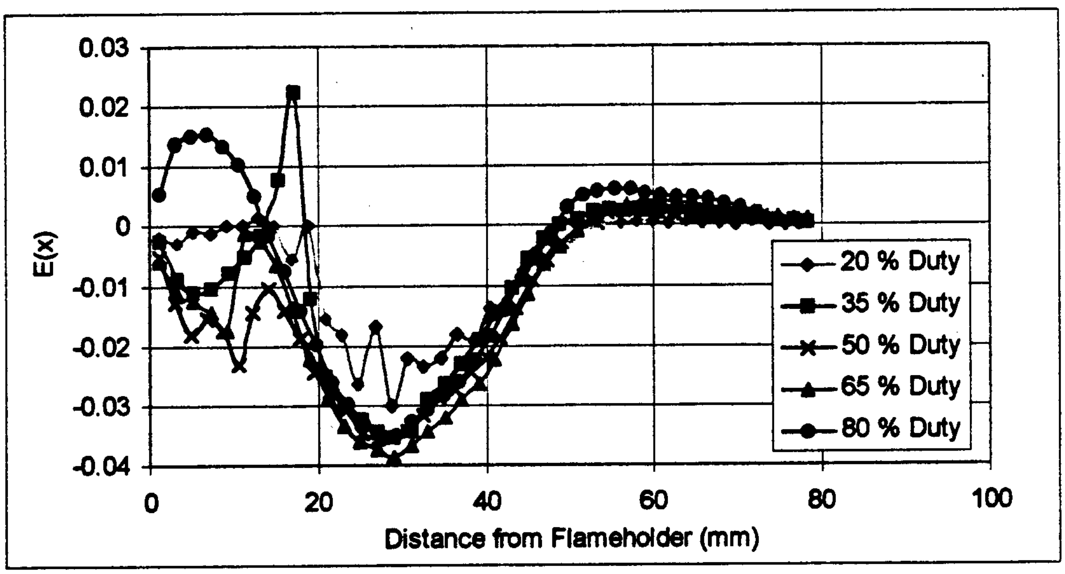
b)

Figure 11: The Effect of Duty Cycle on Modulated Spray Characteristics. Cold Flow Results: measurements were taken 18 mm from the flame-holder on the spray centerline with 170 Hz Square Wave Modulation

a) Droplet Size Distribution
b) Droplet Velocity Distribution



a)



b)

Figure 12: Local Effectiveness of the Control Flames vs. Distance from the Flame-holder

a) 170 Hz Square Wave Modulation
b) 630 Hz Square Wave Modulation

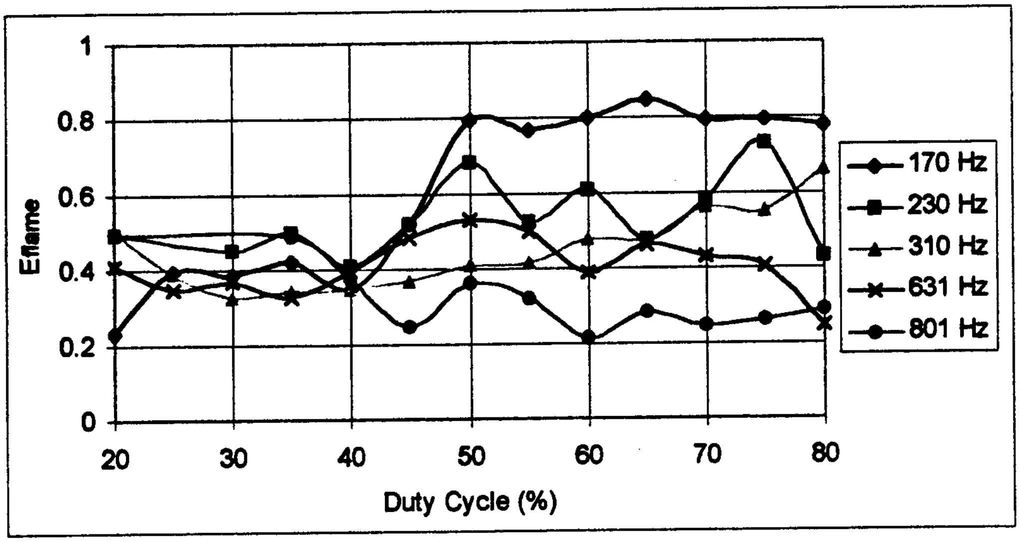


Figure 13: The Influence of Frequency of Square Wave Modulation and Duty Cycle on the Entire Effectiveness of the Control Flames.

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13. ABSTRACT *(Maximum 200 words)*

This study investigated the feasibility of active control of combustion instabilities in liquid fueled combustors using a liquid fuel injector actuator and adaptive control of combustion instabilities. Two different liquid fuel injector actuators were developed and their performance was investigated in open and closed loop active control tests. The open loop tests have shown that these actuators can effectively produce coherent, large amplitude, heat release oscillations with nearly constant phase over a wide range of frequencies, thus indicating that they could be employed to damp combustion instabilities. Furthermore, cold and reactive flow tests have shown that the performance of the liquid fuel actuators depends upon the injector's design and the characteristics of its spray. In parallel efforts, an adaptive control approach that does not require *apriori* knowledge of the open loop response of the control system is being investigated. This system "forces" the unstable combustor with a controlled, slowly varying, disturbance and uses the measured response of the combustor to determine the optimum control system phase and gain. Initial results obtained with this system are promising. This study also investigated the use of piezoelectric actuators to drive the fuel injector actuators in an effort to reduce their size and weight.

14. SUBJECT TERMS
liquid fuel injector actuator, combustion instabilities, piezoelectric actuators

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